Cloud-Radiation Interactions, and Climate Modelling : Problems and Prospects

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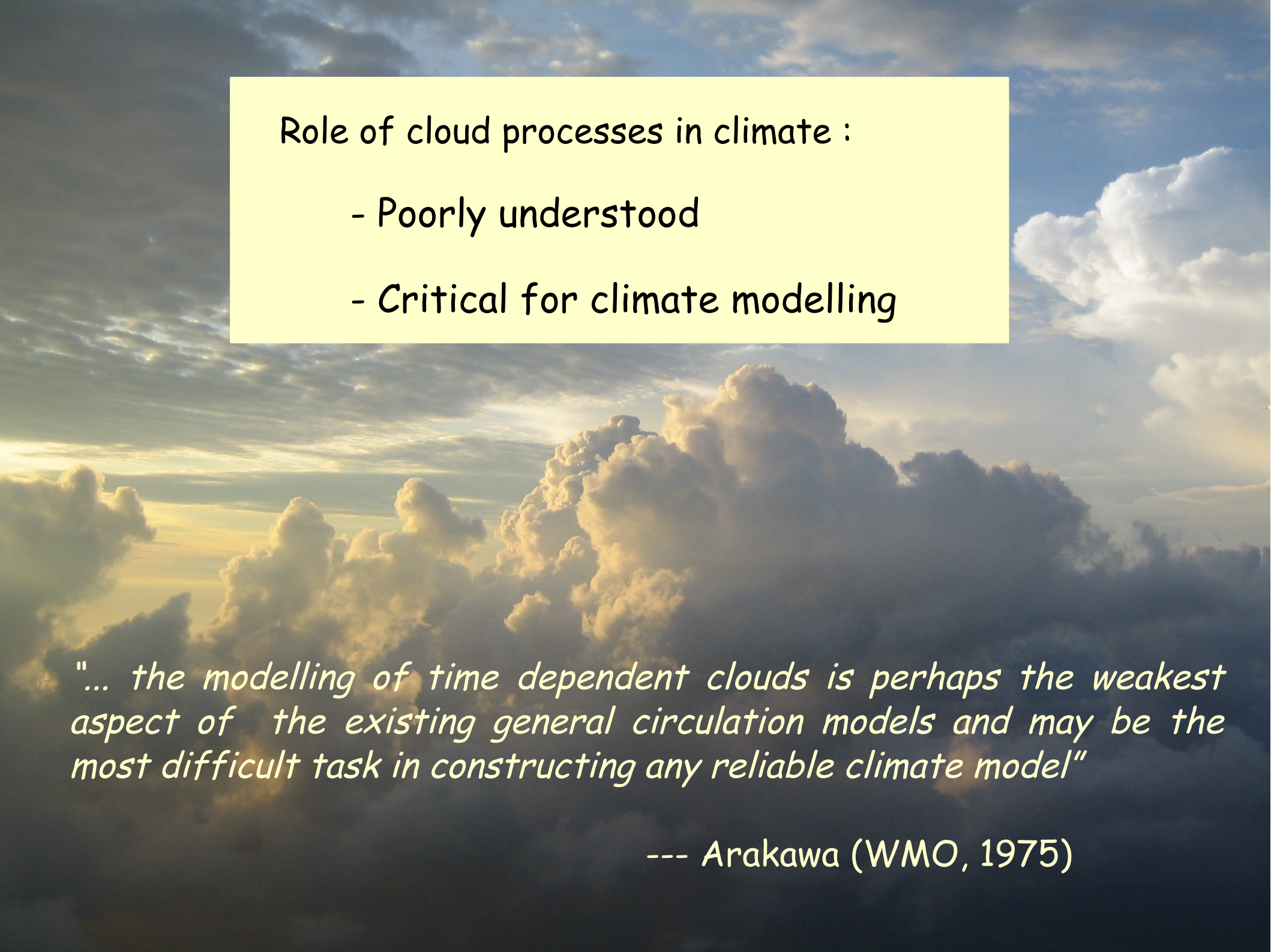
Earth Radiation Budget Workshop 2010
13-16 September 2010



Role of cloud processes in climate :

- Poorly understood

- Critical for climate modelling

"... the modelling of time dependent clouds is perhaps the weakest aspect of the existing general circulation models and may be the most difficult task in constructing any reliable climate model"

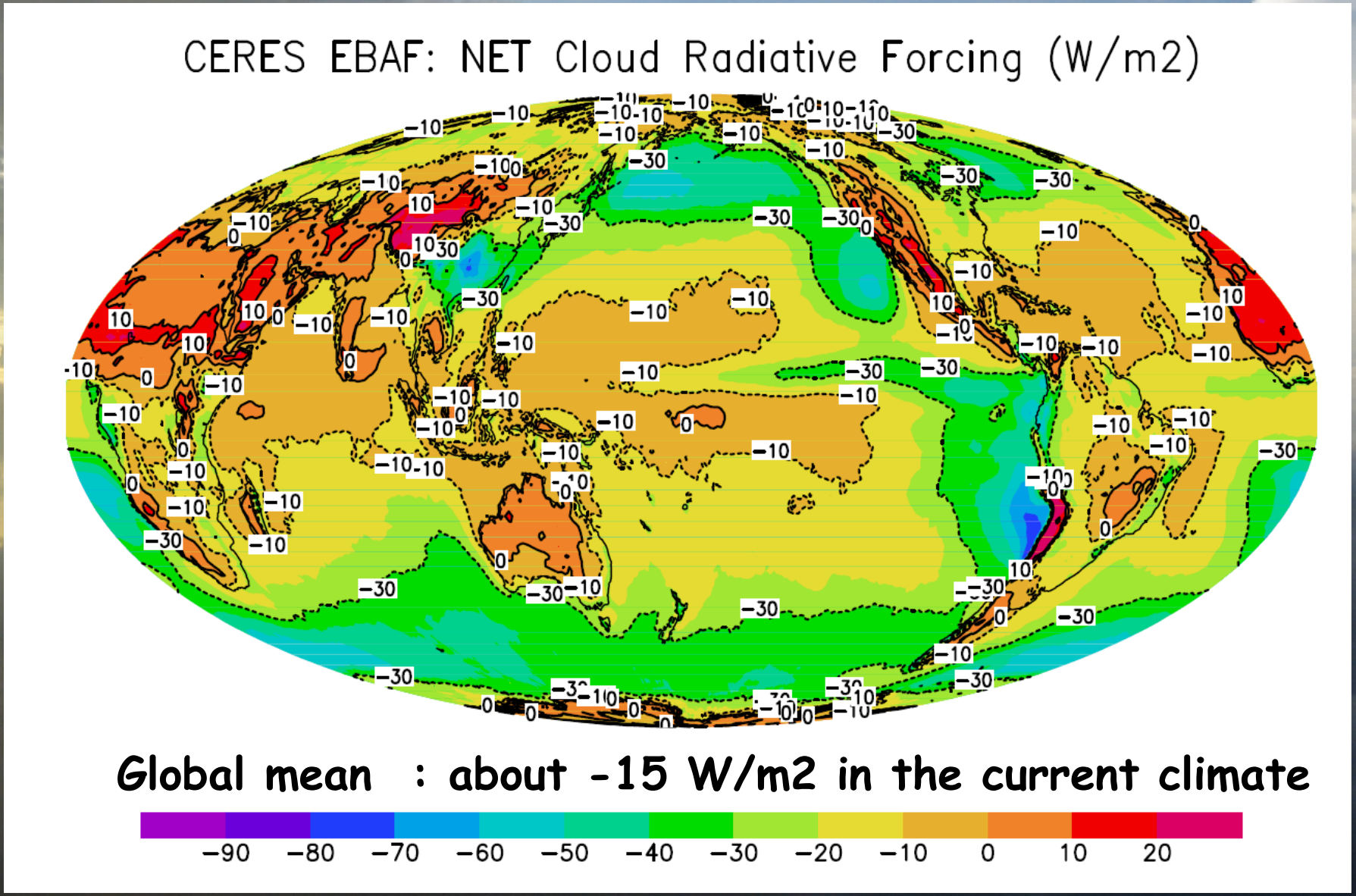
--- Arakawa (WMO, 1975)

Outline :

I - Why are cloud-radiative effects so critical for climate modelling ?

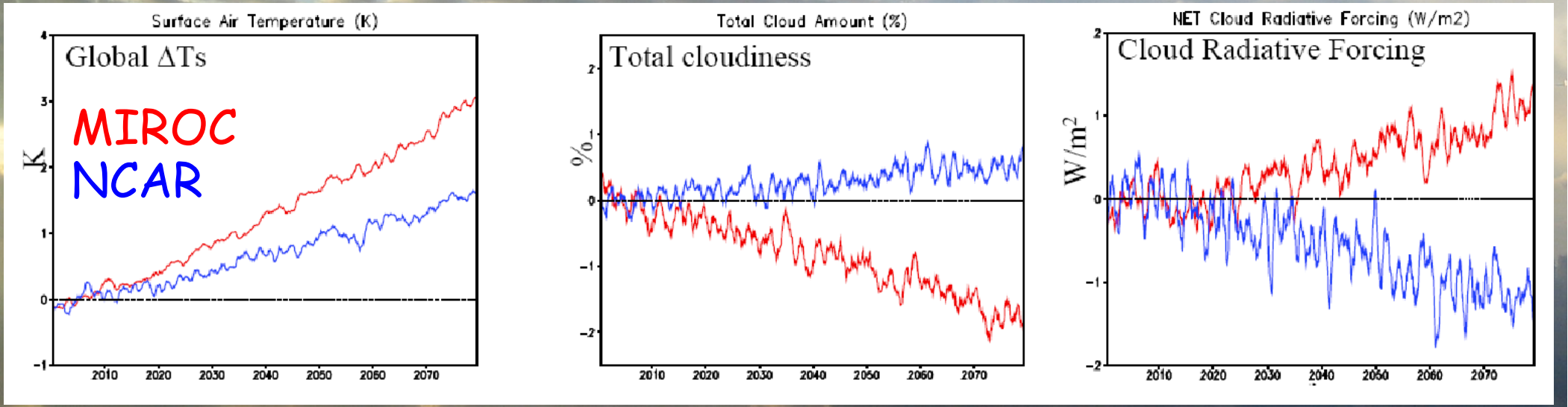
II – What strategies for the evaluation of cloud-climate feedbacks in general circulation models ?

Impact of clouds on the Earth's Radiation Budget (Cloud Radiative Forcing or CRF)

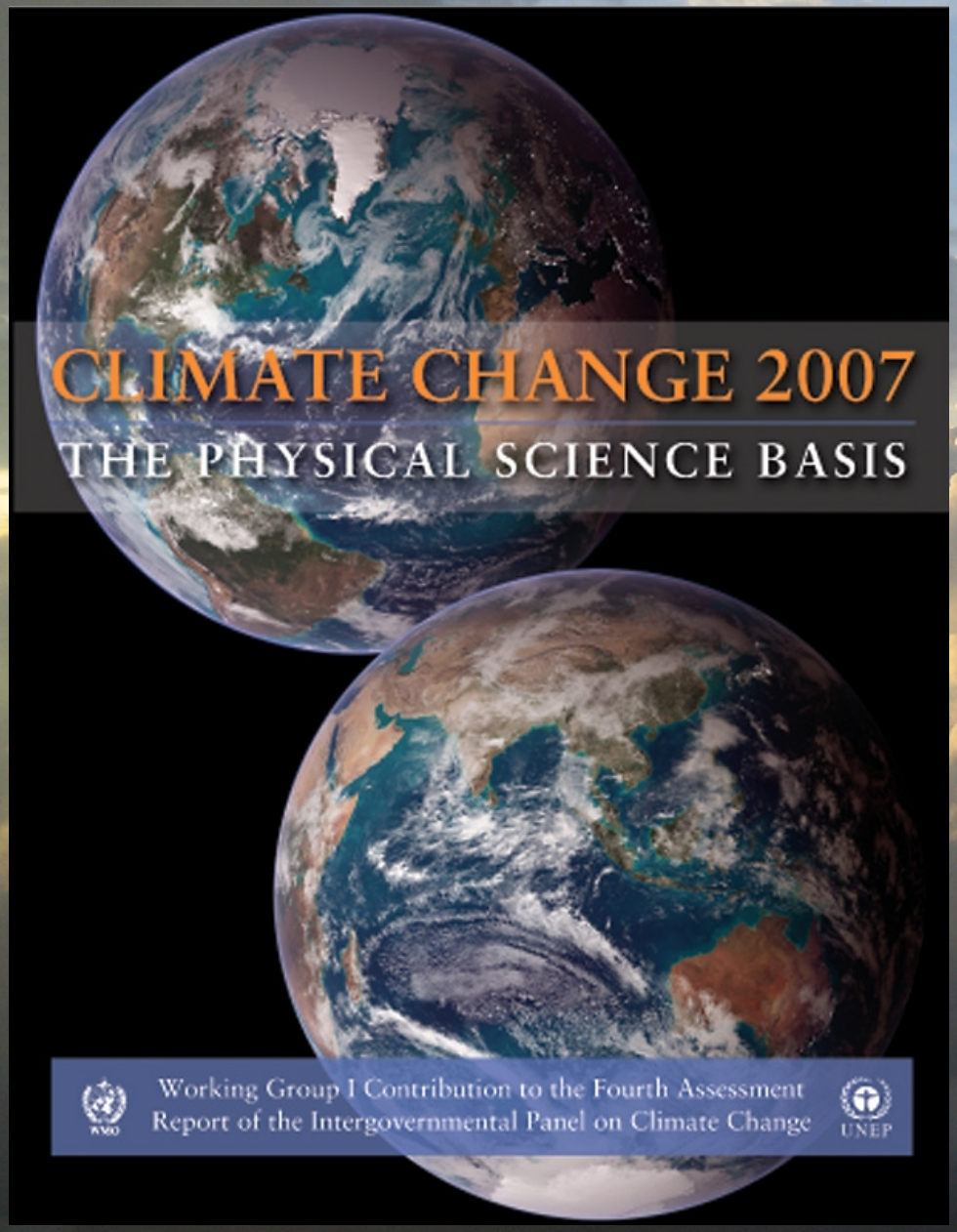


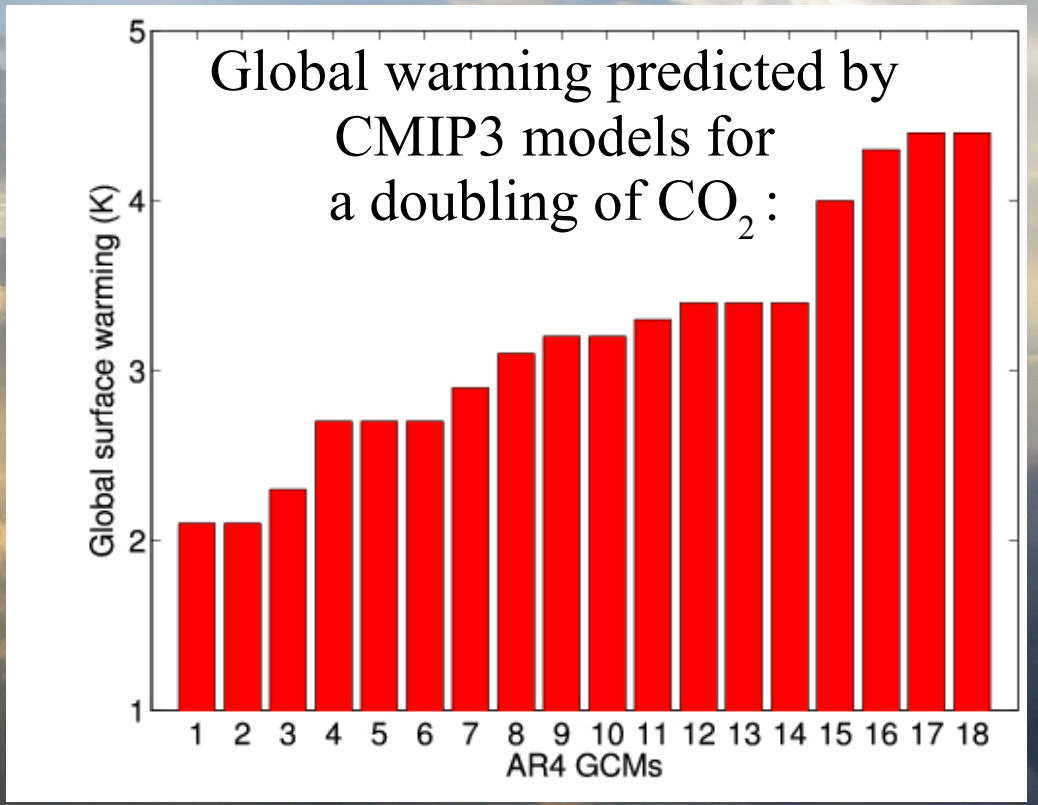
Clouds & Climate Change :

Projections from 2 different climate models (NCAR vs MIROC)



Uncertainty on climate sensitivity





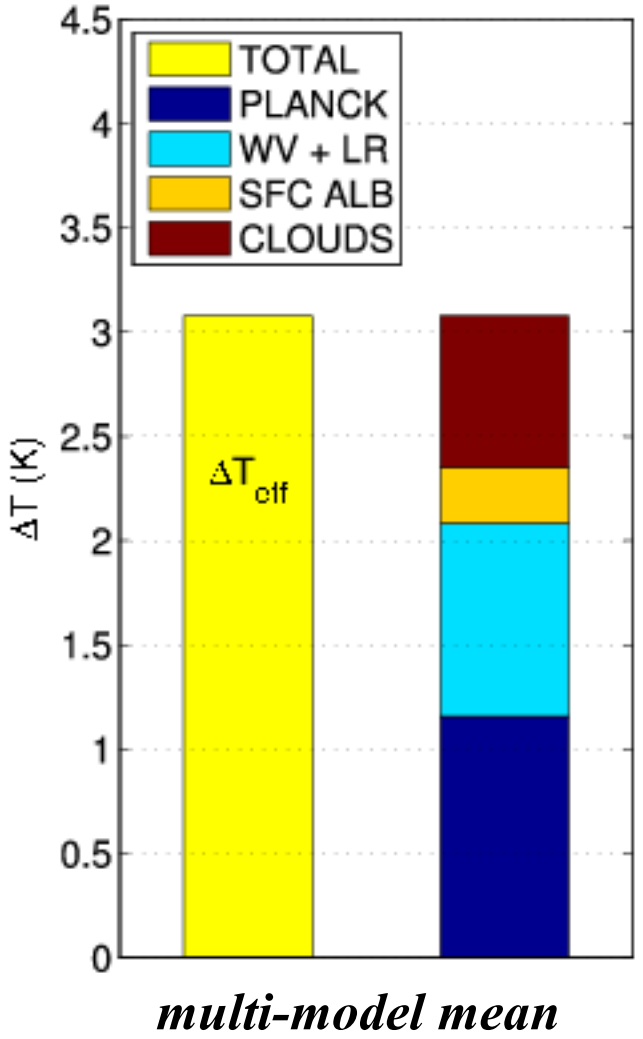
Randall et al., IPCC 2007

Analysis of the uncertainty in climate sensitivity

$$\Delta T_s = \Delta T_{s,P} + \sum_{x \neq P} \Delta T_{s,x}$$

Planck response

Feedback contributions



multi-model mean

cloud feedback

snow& sea-ice feedback

water vapor + lapse rate feedback

basic Planck response

(Dufresne and Bony, J. Climate, 2008)

Analysis of the uncertainty in climate sensitivity

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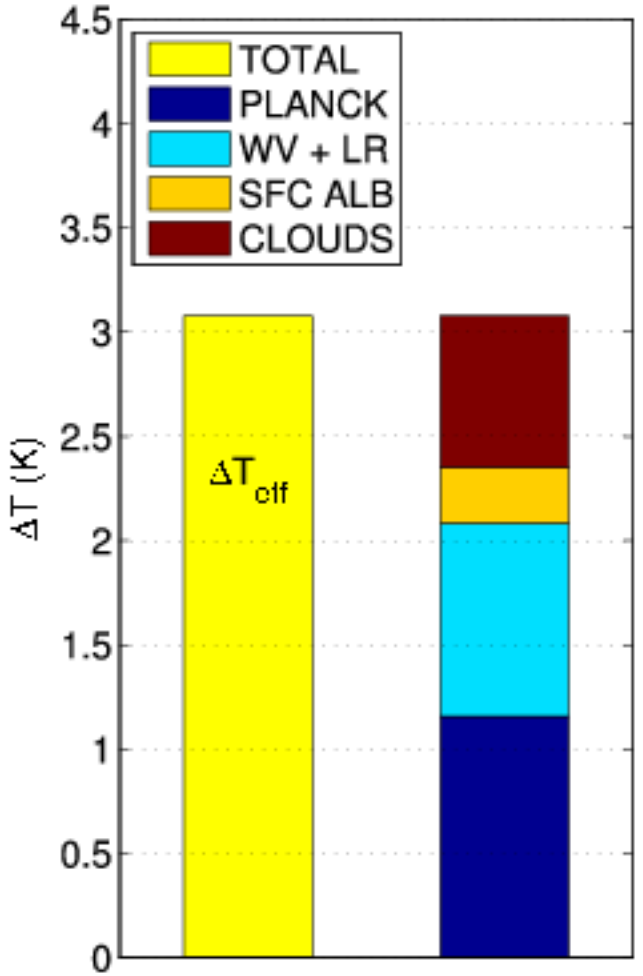
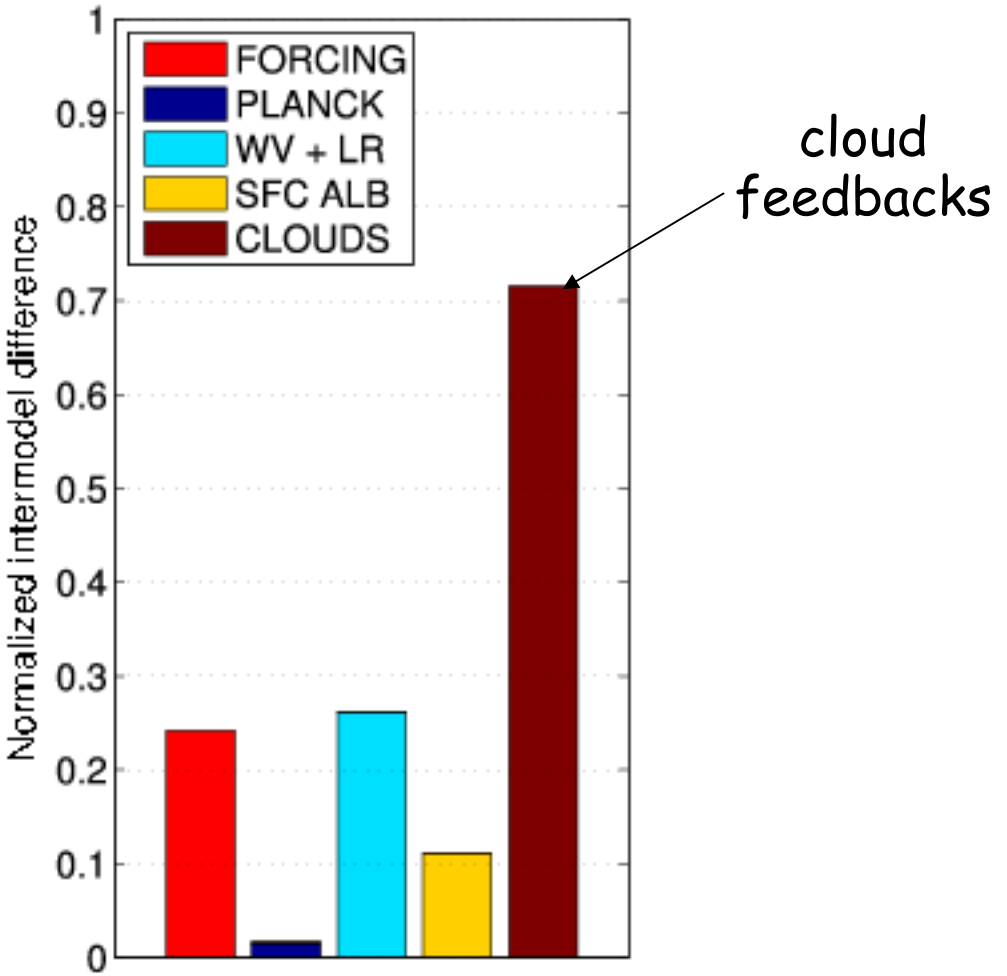
Planck response

Feedback contributions



multi-model mean



inter-model differences (standard deviation)

(Dufresne and Bony, J. Climate, 2008)

"Cloud feedbacks remain the primary source of uncertainty in model based estimates of climate sensitivity. "

--- IPCC AR4 (2007)

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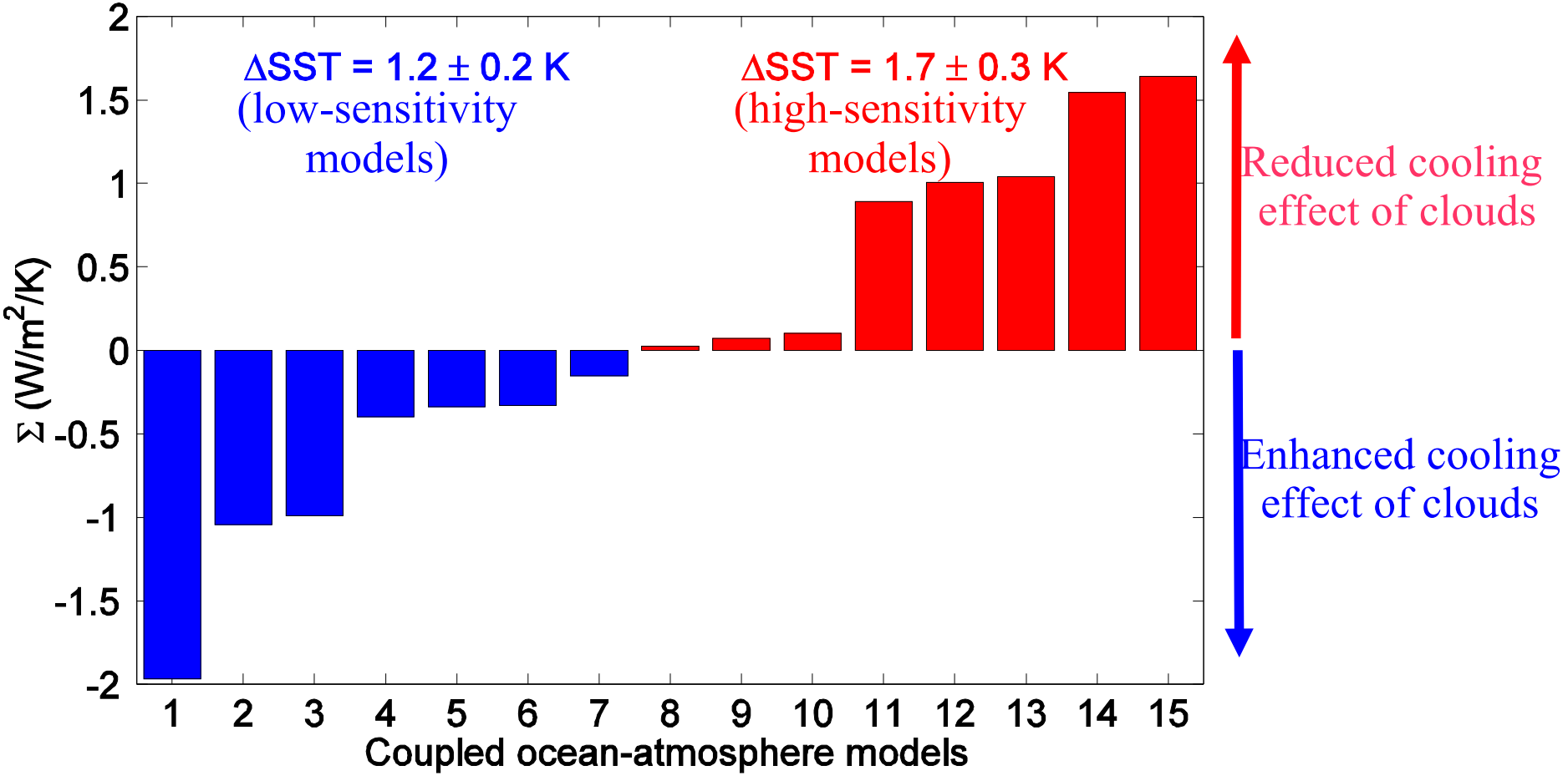
--- IPCC AR4 (2007)

→ Where does this uncertainty come from ?

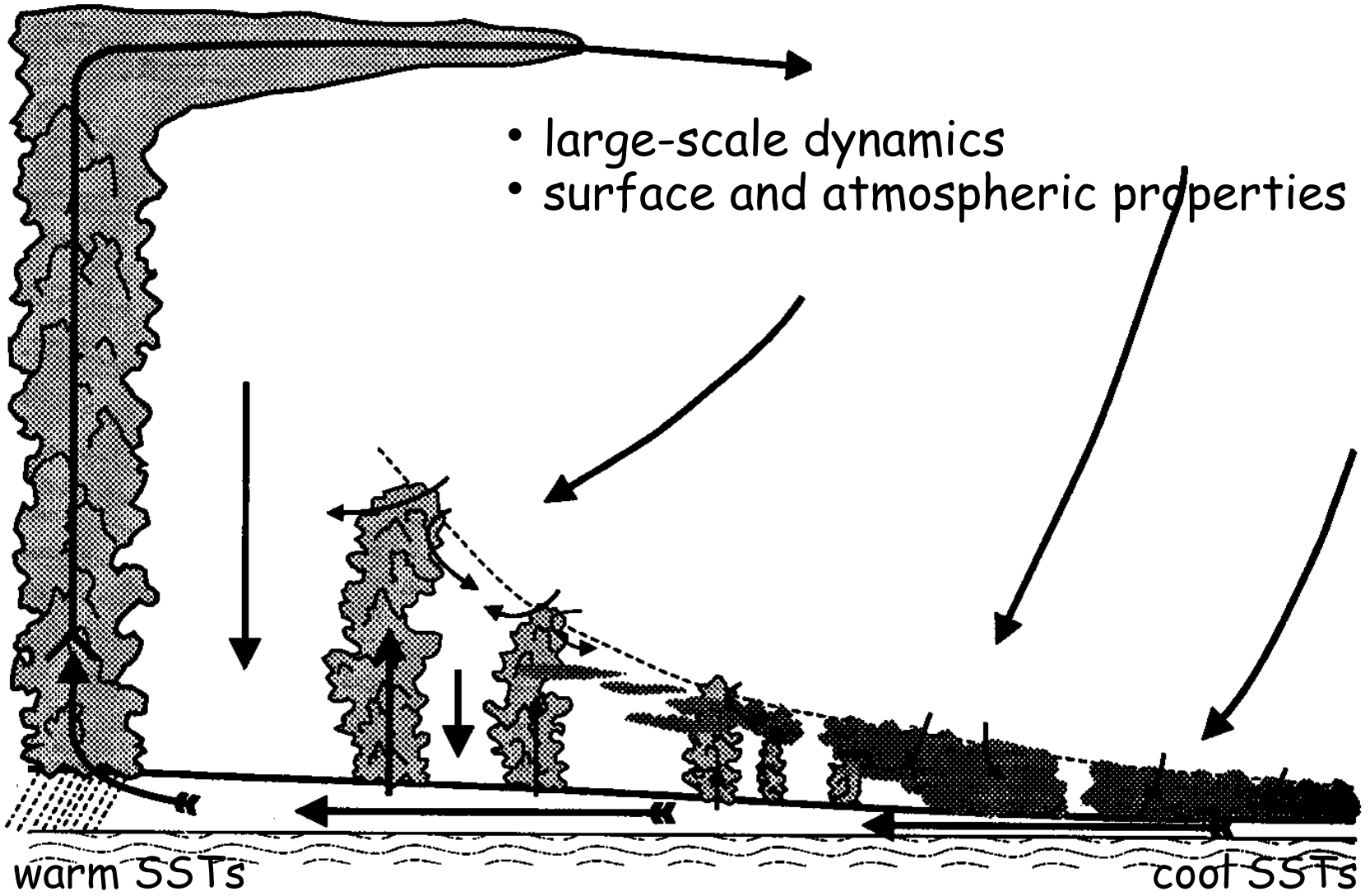
15 CMIP3/AR4 Coupled Ocean-Atmosphere GCMs (+1% CO2/year experiments)

Sensitivity of the tropical NET CRF to global warming ($W/m^2/K$)



(Bony and Dufresne, GRL, 2005)

What controls the response of tropical clouds to climate change ?

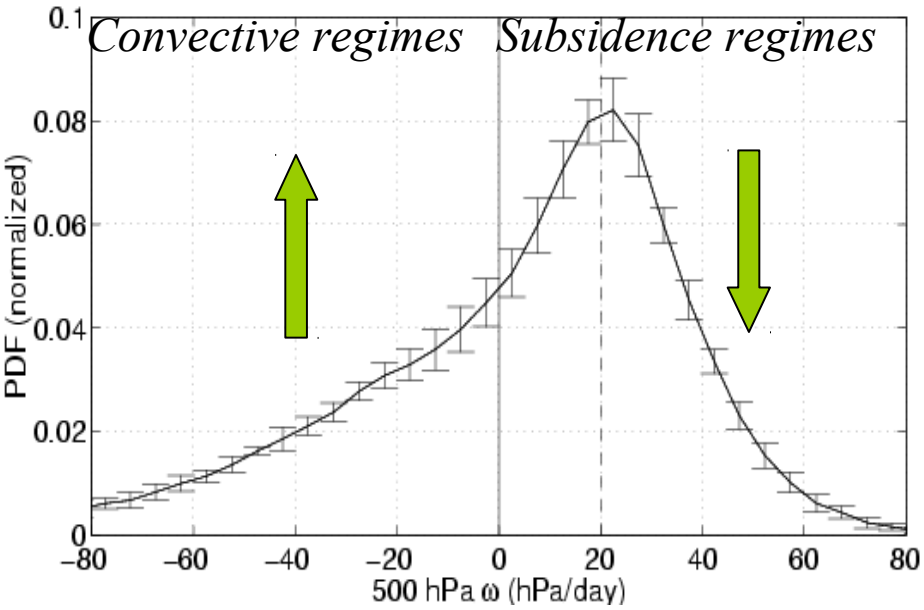


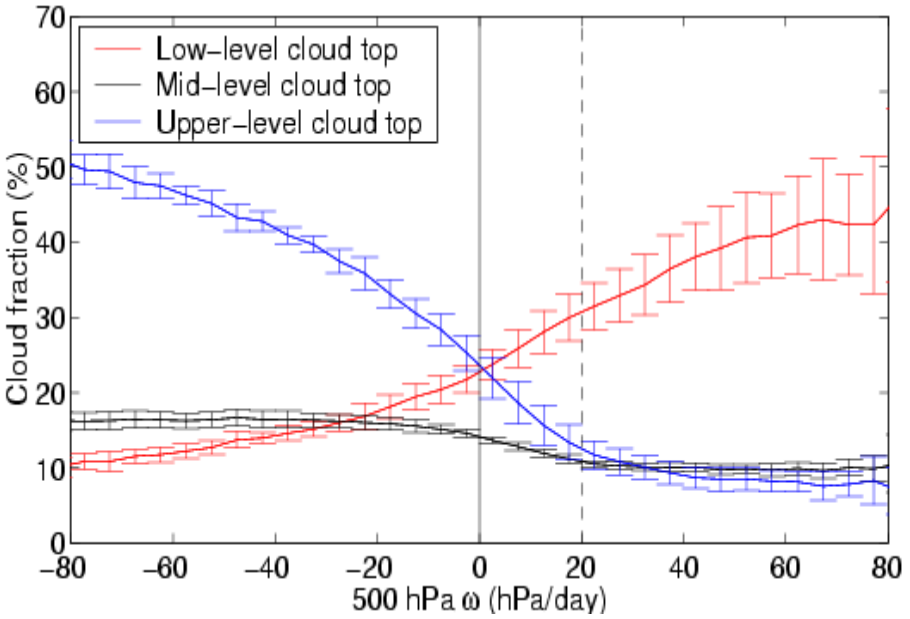
(Emanuel, 1994)

Sensitivity of the Tropical Cloud Radiative Forcing to Global Warming

Analysis method :

- Proxy ω for large-scale motions: ω_{500hPa}.
- Decomposition of the tropical circulation into dynamical regimes: $\int_{-\infty}^{+\infty} P_\omega \, d\omega = 1$
- Composite of cloud or radiative variables in each dynamical regime: C_ω
- Tropical average: $\overline{C} = \int_{-\infty}^{+\infty} P_\omega \, C_\omega \, d\omega$





(Bony et al. 2004; Bony and Dufresne, 2005)

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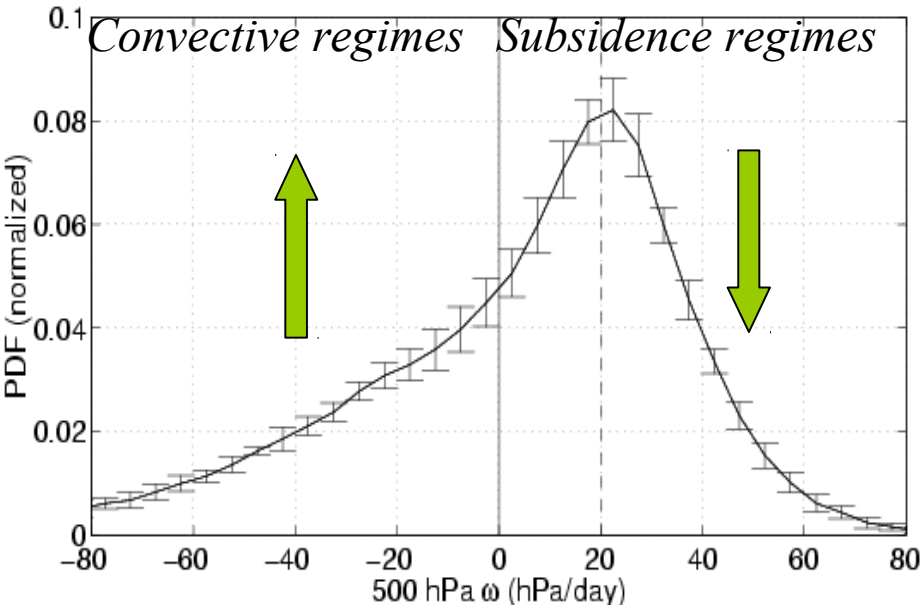

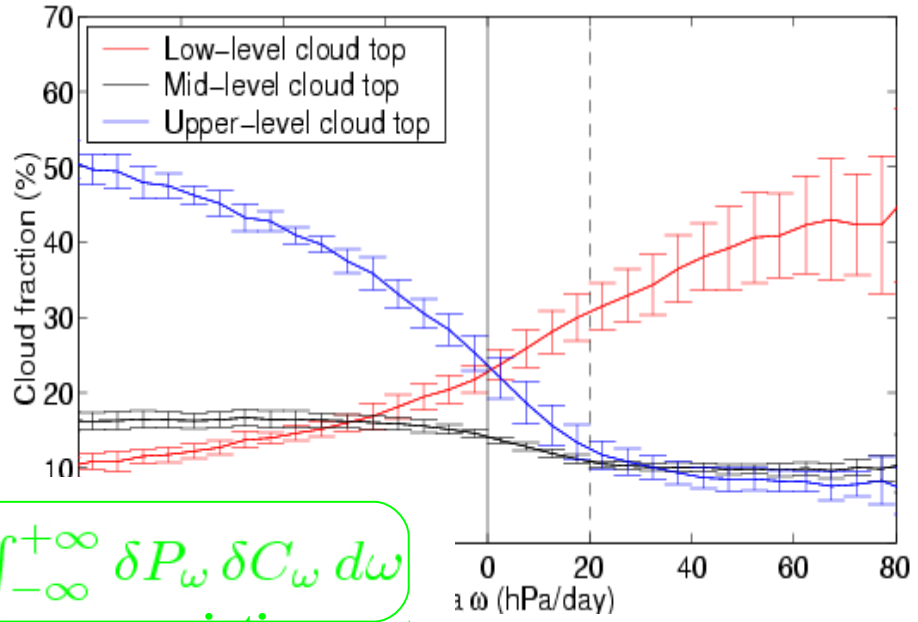

$$\overline{\delta C} = \underbrace{\int_{-\infty}^{+\infty} C_\omega \, \delta P_\omega \, d\omega}_{\text{dynamic component}} + \underbrace{\int_{-\infty}^{+\infty} P_\omega \, \delta C_\omega \, d\omega}_{\text{thermodynamic component}} + \underbrace{\int_{-\infty}^{+\infty} \delta P_\omega \, \delta C_\omega \, d\omega}_{\text{co-variation}}$$

Sensitivity of the Tropical Cloud Radiative Forcing to Global Warming

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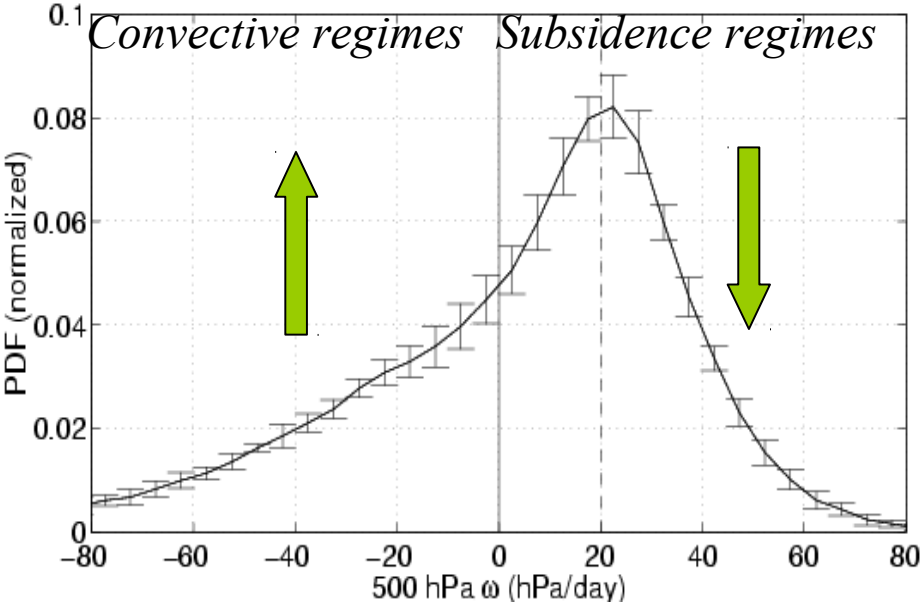
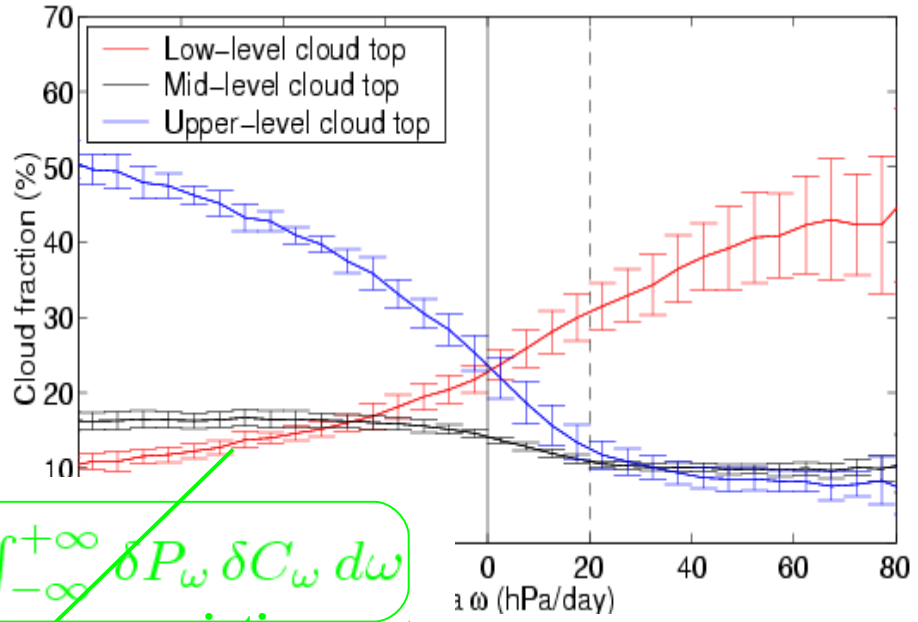
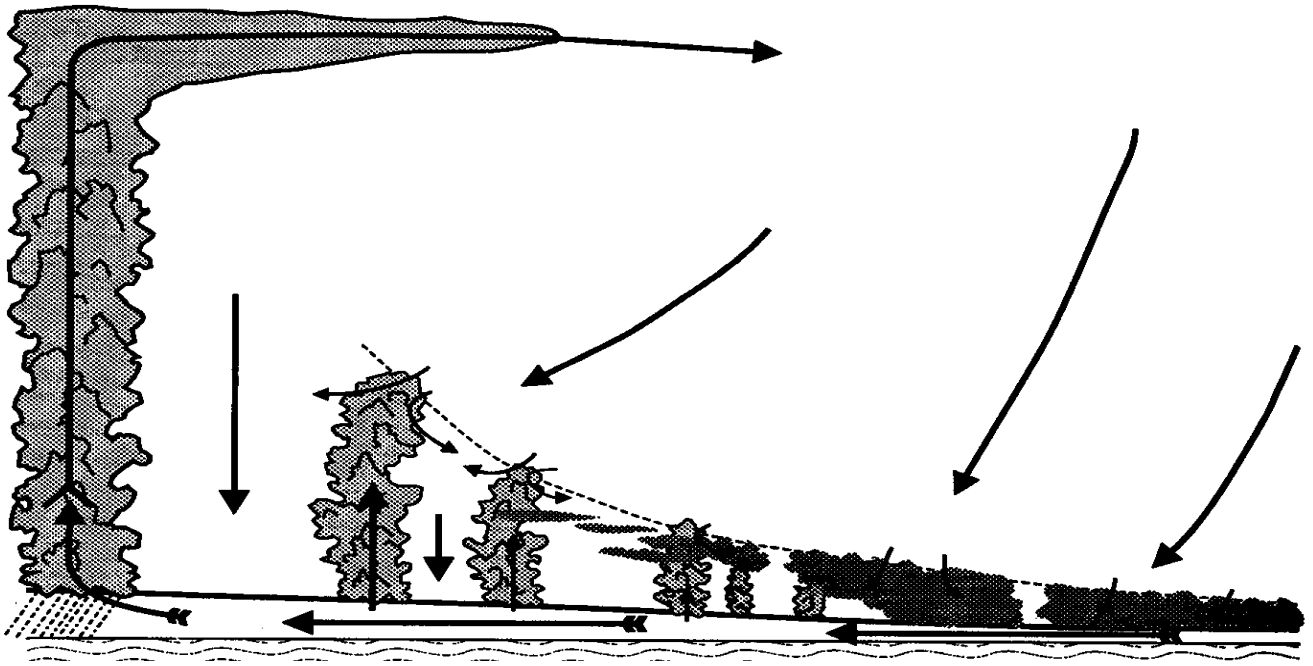


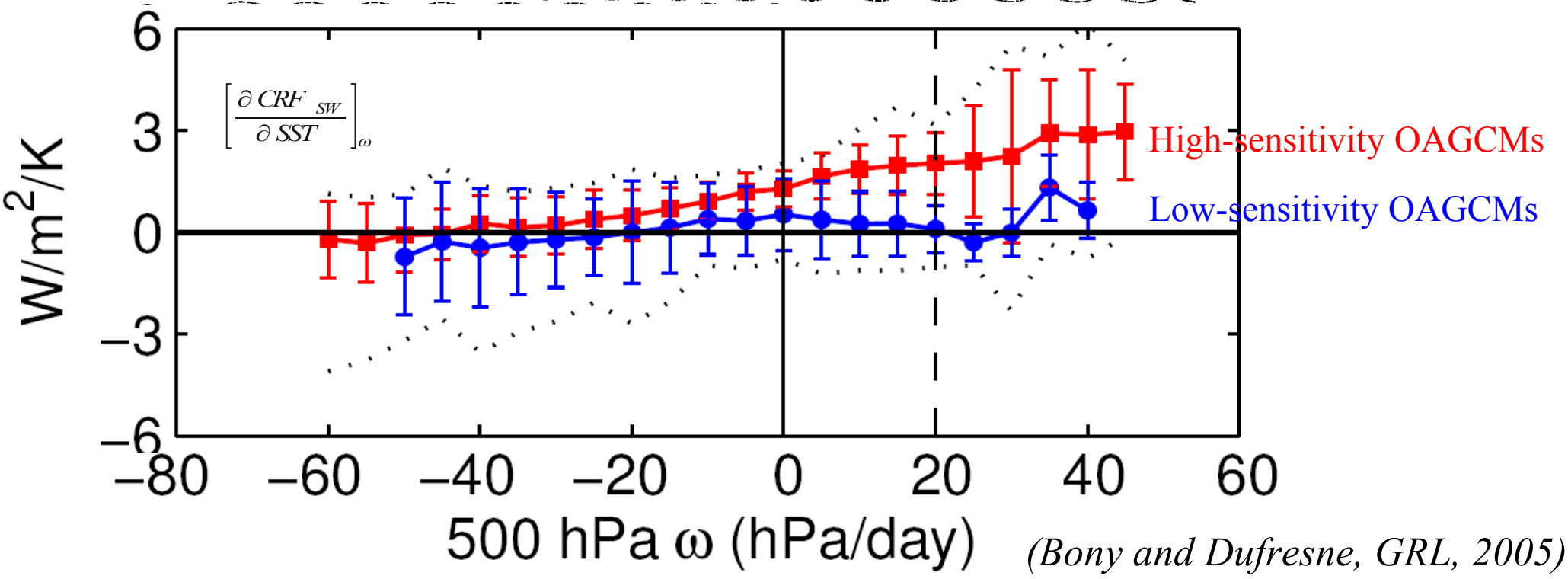


$$\overline{\delta C} = \int_{-\infty}^{+\infty} C_\omega \, \delta P_\omega \, d\omega + \int_{-\infty}^{+\infty} P_\omega \, \delta C_\omega \, d\omega + \int_{-\infty}^{+\infty} \delta P_\omega \, \delta C_\omega \, d\omega$$

dynamic component | **thermodynamic component** | **co-variation**

Sensitivity of the Tropical Cloud Radiative Forcing to Global Warming

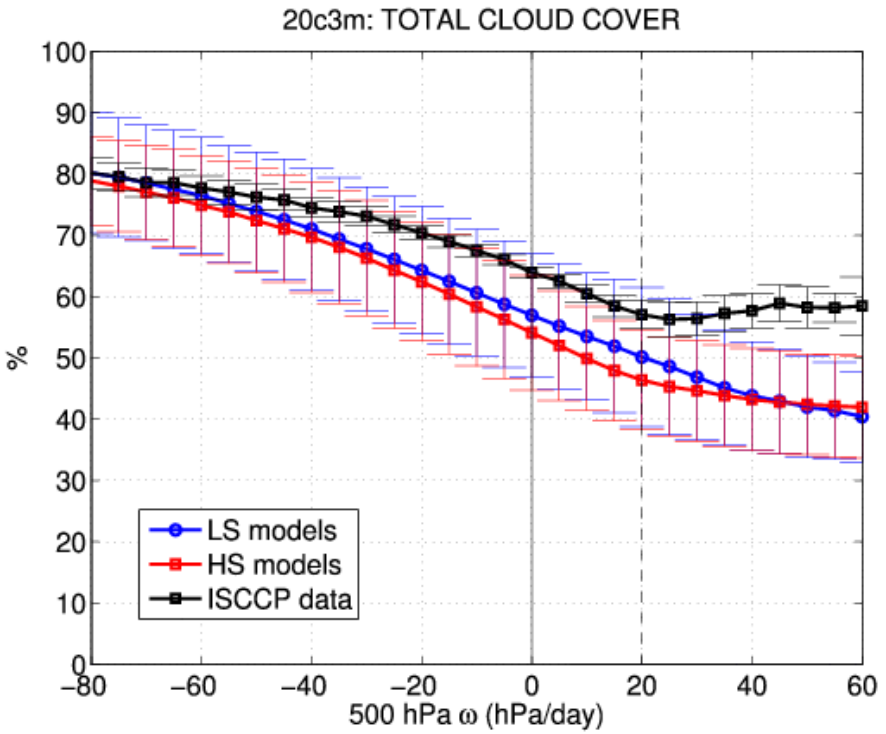


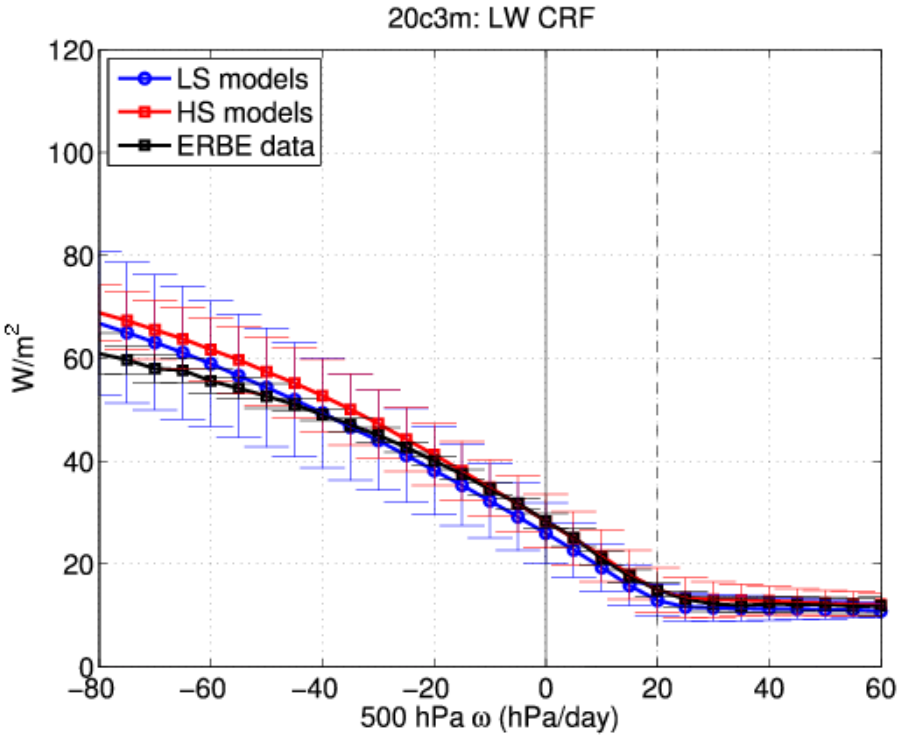


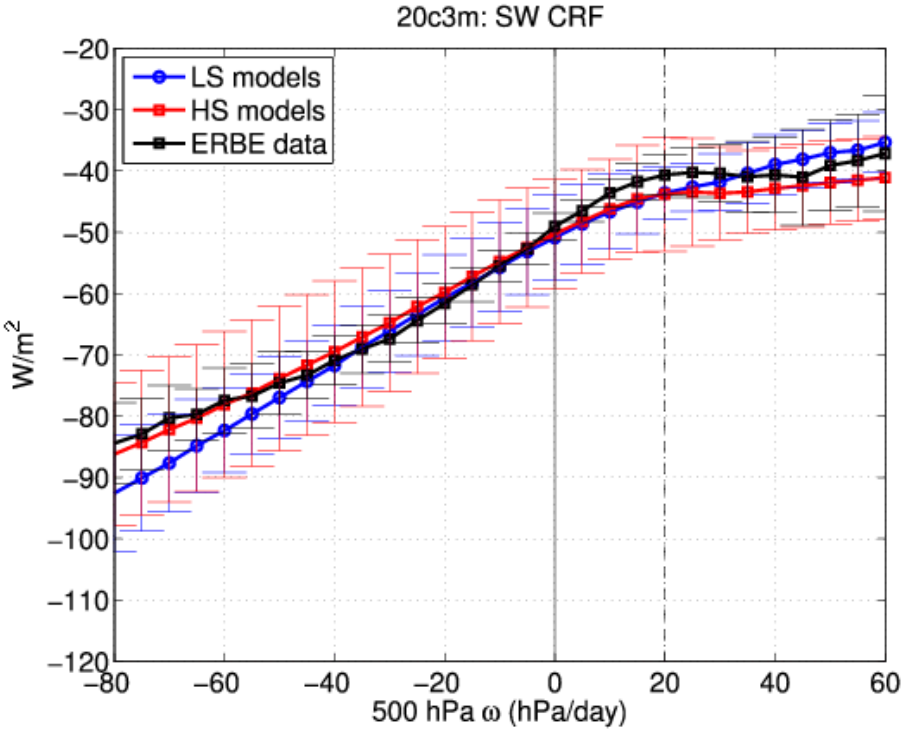
(Bony and Dufresne, GRL, 2005)

Mean cloud properties simulated by low-sensitivity and high sensitivity GCMs in the current climate (CMIP3 OAGCMs)

- High-sensitivity GCMs (8 OAGCMs)
- Low-sensitivity GCMs (7 OAGCMs)
- Observations







The response of marine boundary-layer clouds has been pointed out as a primary contributor to inter-model differences in climate sensitivity (Randall et al., IPCC 2007).

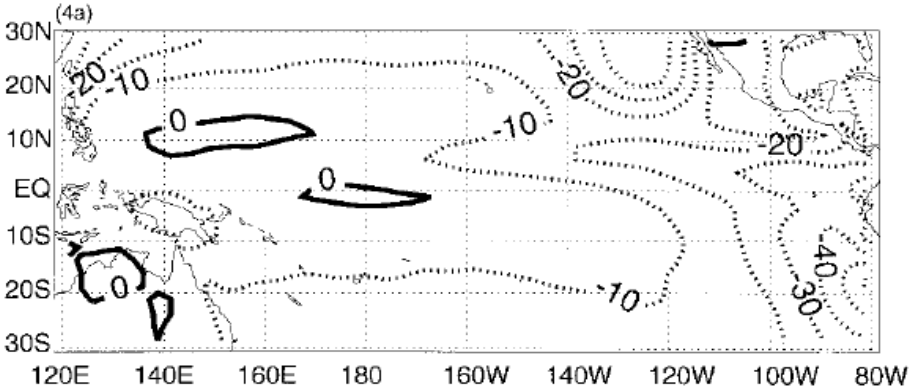
However :

- Clouds do not matter only for climate sensitivity !

- PBL clouds are not the only clouds to be critical for climate modelling !

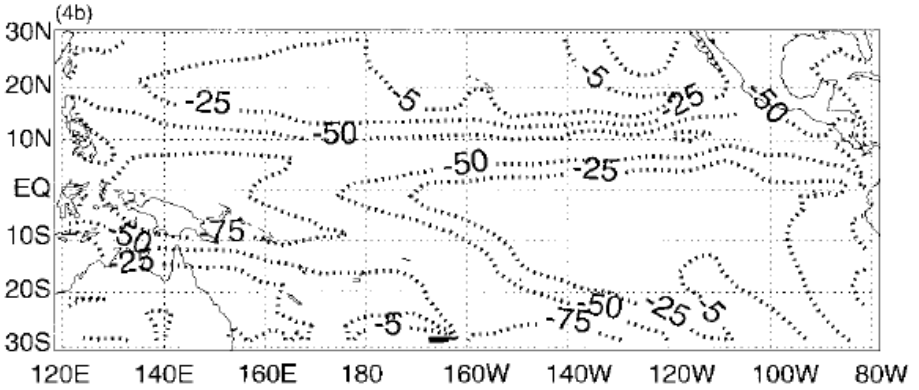
Cloud-Radiative Effects in the Tropics

Deep convective clouds have a weak impact on NET radiation TOA, but ...



TOA CRF (W/m2)

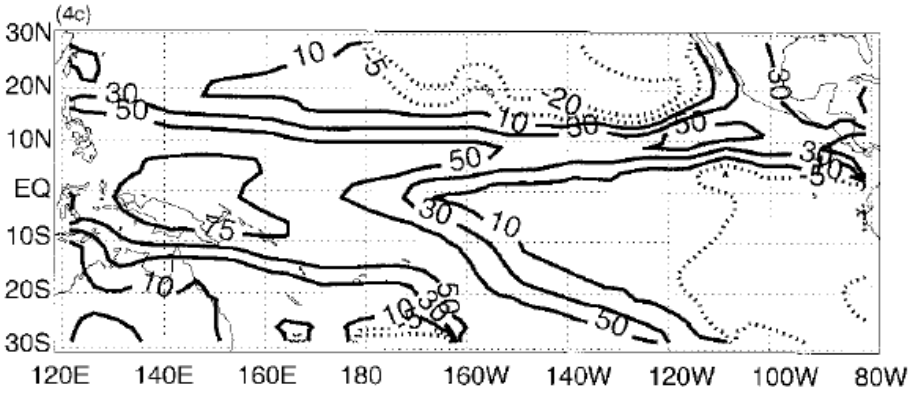
cool the surface (by increasing the albedo)



Surface CRF (W/m2)

and

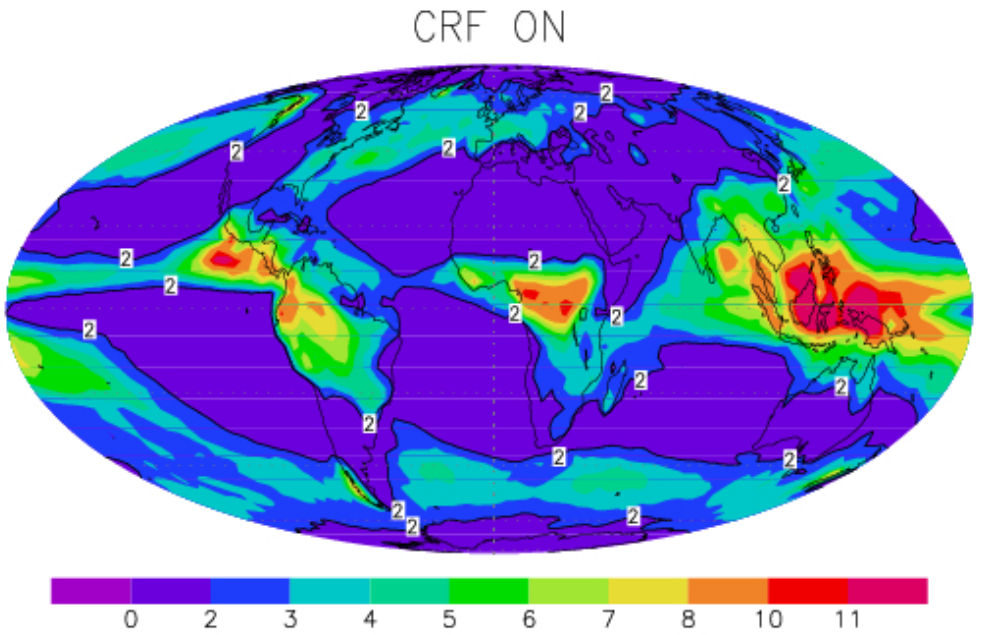
warm the troposphere (by reducing the radiative cooling)



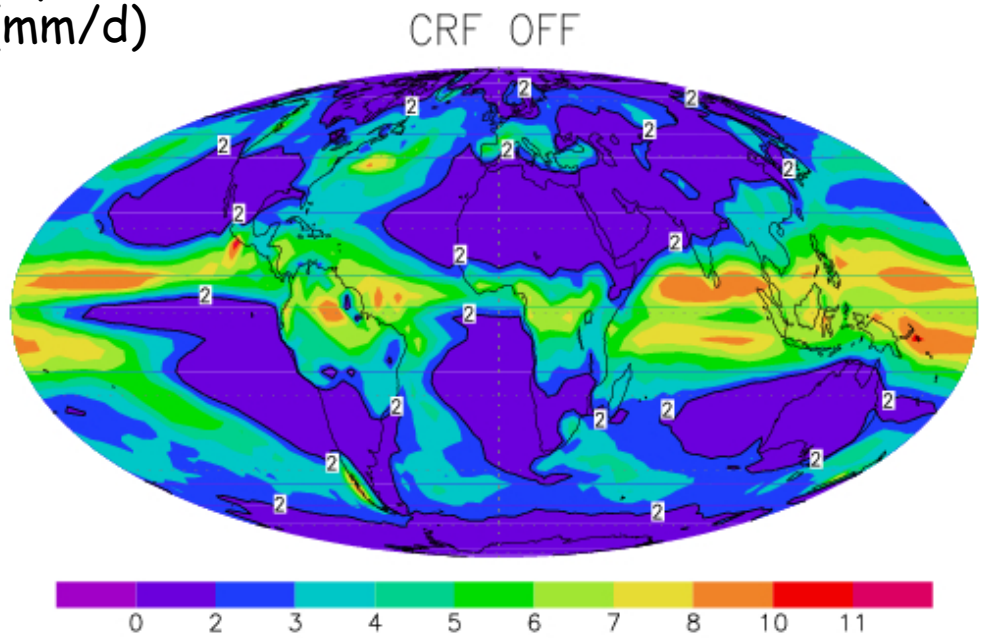
Tropospheric CRF (W/m2)

(Tian & Ramanathan 2002)

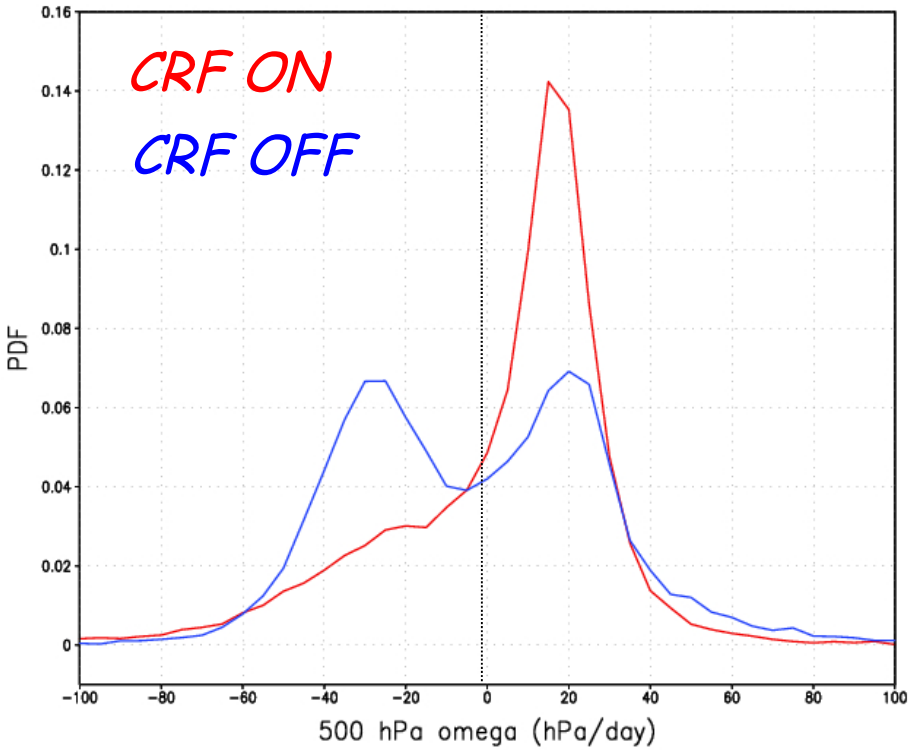
Impact of the atmospheric cloud radiative forcing on GCM-simulated tropical circulation



Precipitation (mm/d)



PDF of 500hPa omega

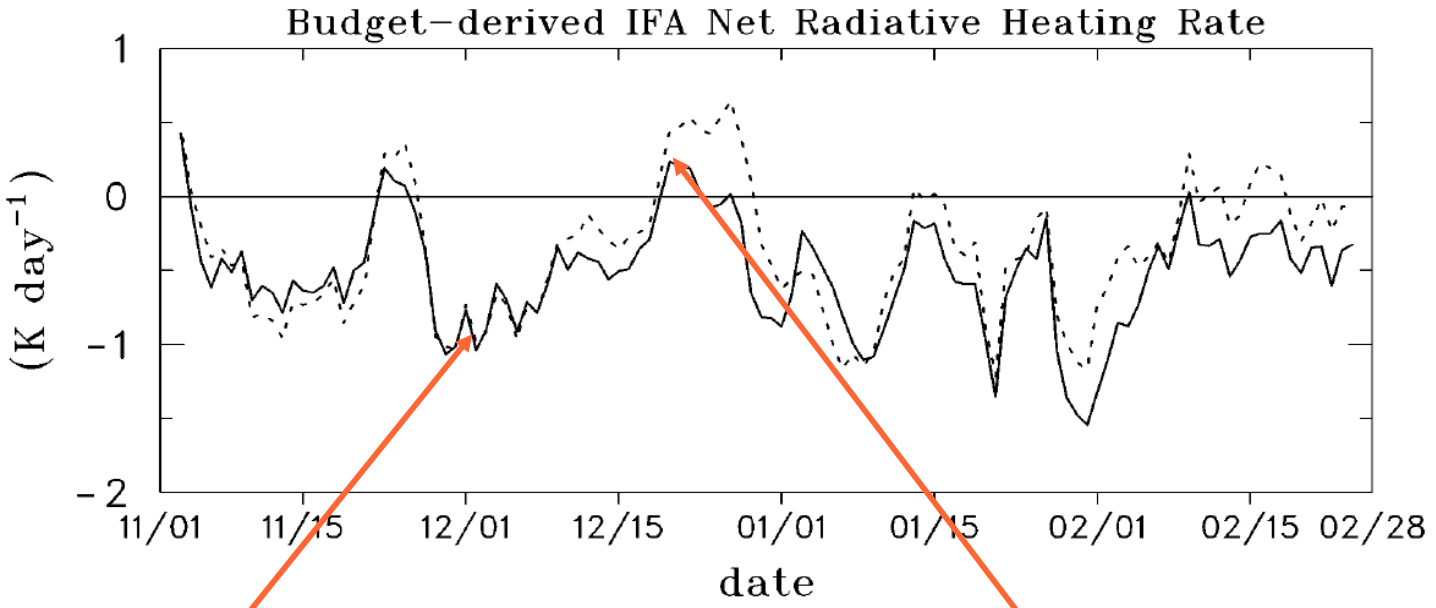


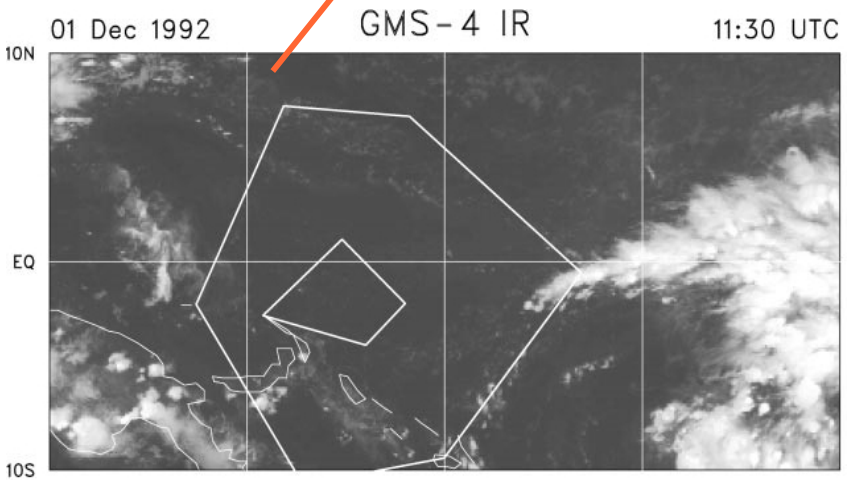
Cloud-radiative effects strengthen the Hadley-Walker circulation and make the ITCZ more narrow

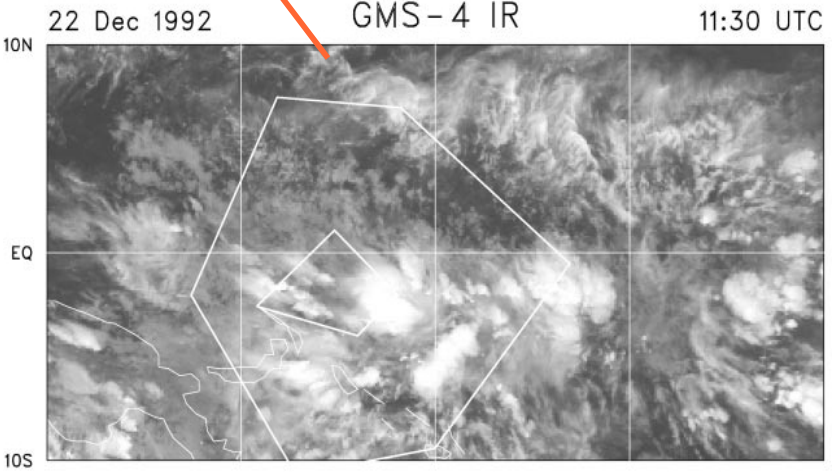
TOGA COARE :

Tropospheric Radiative Heating Rate

(Johnson and Ciesielski, JAS, 2000 ; Ciesielski et al., JAS, 2003)



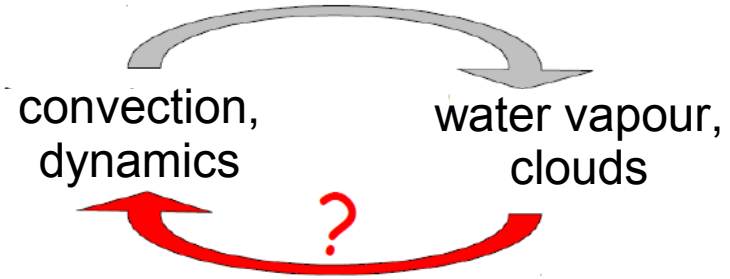


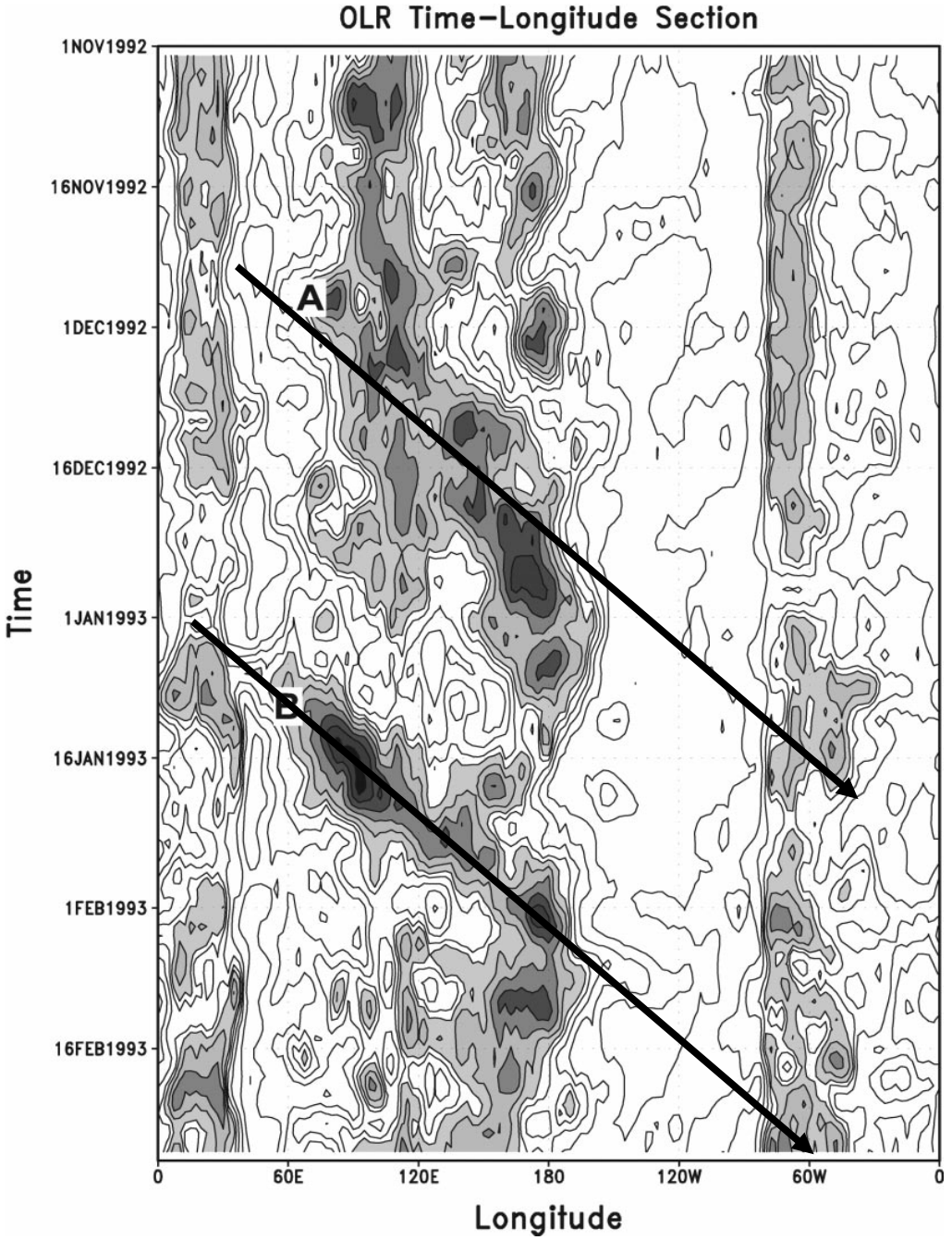


TOGA COARE

Fluctuations of clouds and OLR have long been considered as manifestations of tropical variability,

May cloud-radiation interactions also play an active role in the variability of the tropical atmosphere ?

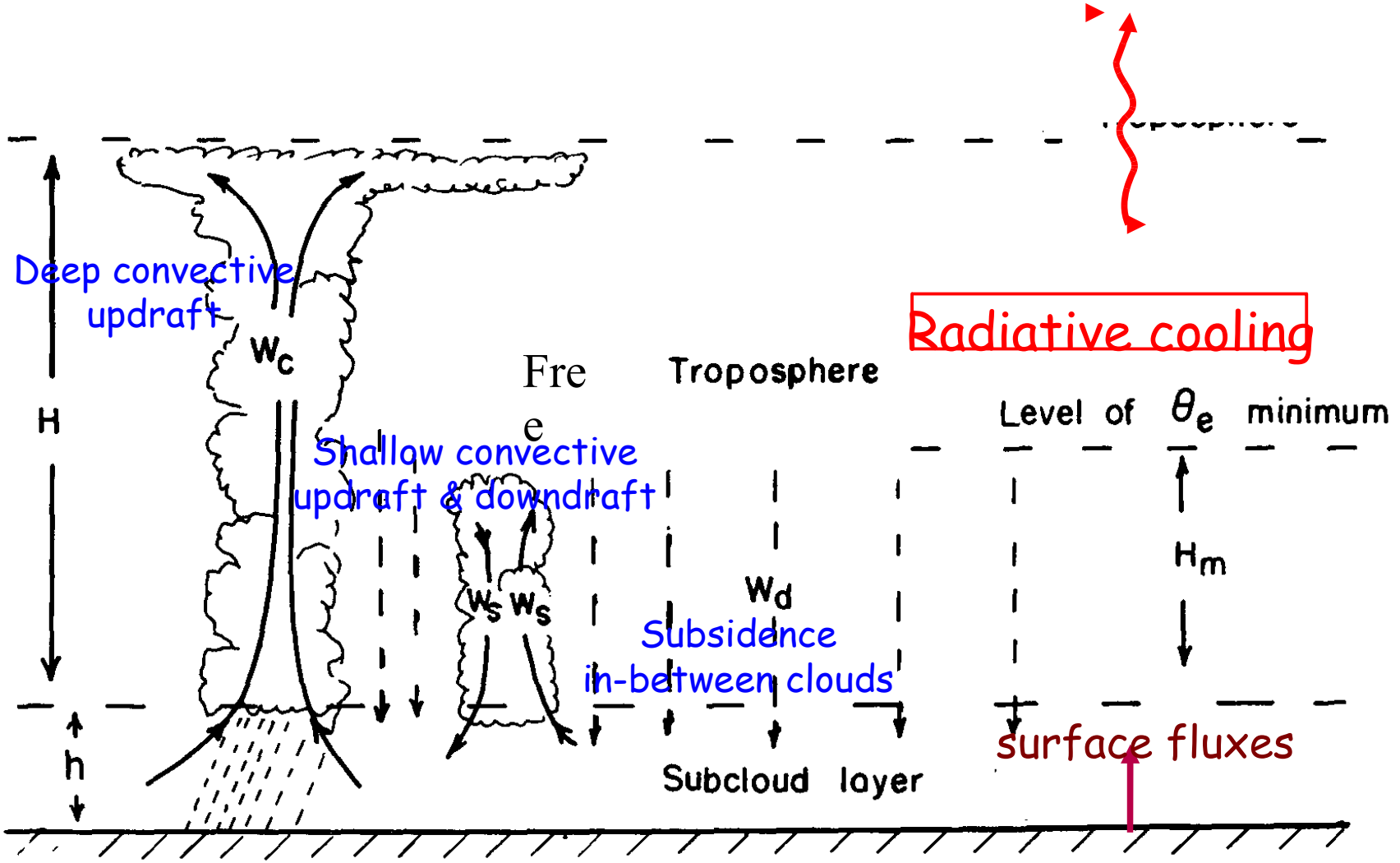




(Yanai et al. 2000)

Simple Linear Model of the Equatorial Atmosphere

(Emanuel 1987, Yano & Emanuel 1991, Bony & Emanuel 2005)



Simple Linear Model of the Equatorial Atmosphere

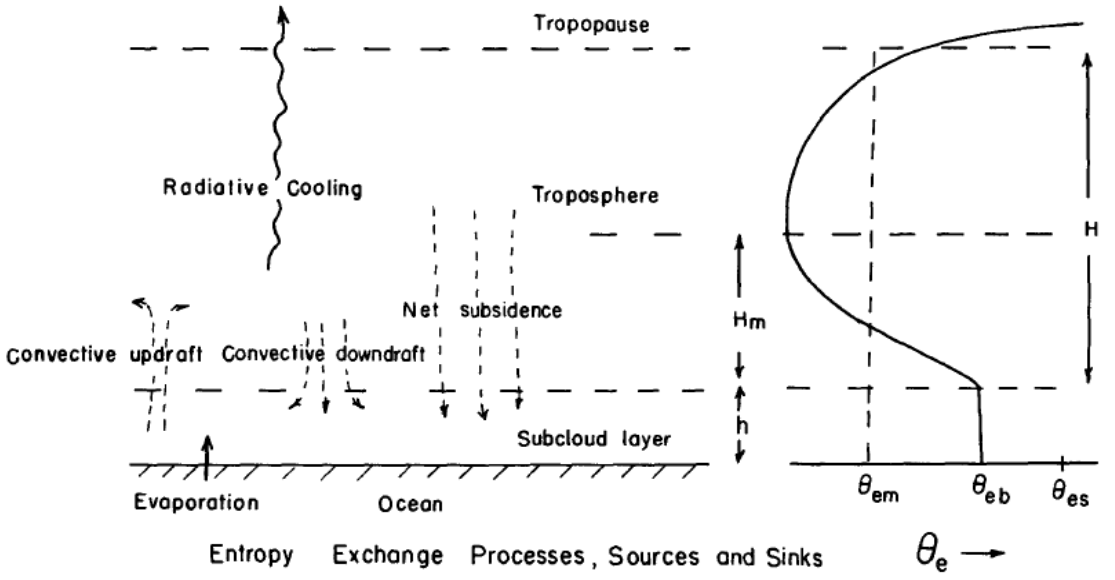
$$\frac{\partial u_b}{\partial x} + \frac{w}{H_m} = 0$$

$$\left(\frac{\partial}{\partial t} + u_b \frac{\partial}{\partial x}\right) u_b = -\frac{\partial \Phi_b}{\partial x} - \frac{C_d}{h}|\mathbf{V}_b| u_b$$

$$g\left(\frac{\partial}{\partial t} + u_b \frac{\partial}{\partial x}\right) \ln\theta = N^2(-w + \sigma w_c) - g\dot{R}$$

$$h\left(\frac{\partial}{\partial t} + u_b \frac{\partial}{\partial x}\right) \ln\theta_{\mathrm{eb}} = C_k|\mathbf{V}_b|(\ln\theta_{\mathrm{es}} - \ln\theta_{\mathrm{eb}}) + \left(w - \frac{\sigma w_c}{\varepsilon_p}\right)(\ln\theta_{\mathrm{eb}} - \ln\theta_{\mathrm{em}})$$

$$H_f\left(\frac{\partial}{\partial t} + u_b \frac{\partial}{\partial x}\right) \ln\theta_{\mathrm{em}} = -H_f\dot{R} - \left(w - \frac{\sigma w_c}{\varepsilon_p}\right)(\ln\theta_{\mathrm{eb}} - ln\theta_{\mathrm{em}})$$



The tropospheric radiative cooling is parameterized as a function of the moist entropy deficit (proxy for clouds and moisture):

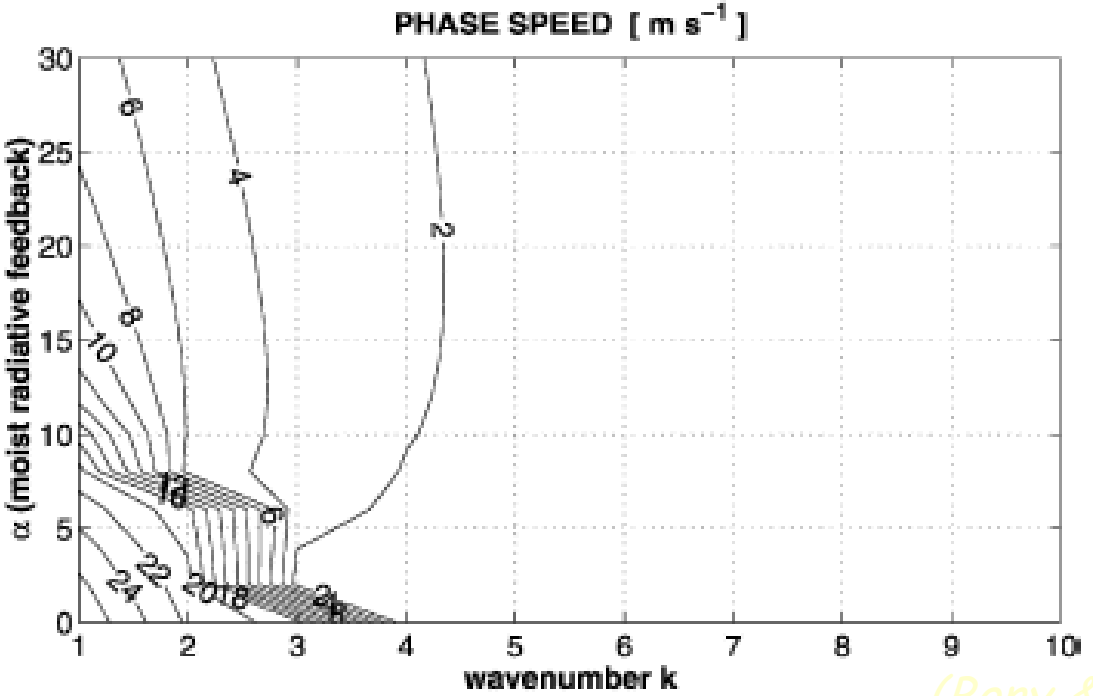
$$\dot{R} = \dot{R}_0\left\{1 + \alpha \frac{\delta(\ln\theta_{\mathrm{eb}} - \ln\theta_{\mathrm{em}})}{[\ln\theta_{\mathrm{eb}} - \ln\theta_{\mathrm{em}}]}\right\}$$

α : positive parameter whose value is specified

Role of moist-radiative feedbacks in the large-scale organization of the equatorial atmosphere

(1) Cloud-radiative feedbacks affect the growth rate of unstable modes of the tropical atmosphere; strong feedbacks excite small-scale disturbances (advected by the mean flow) and thus the relative prominence of small-scale and planetary-scale modes of organization of the atmosphere.

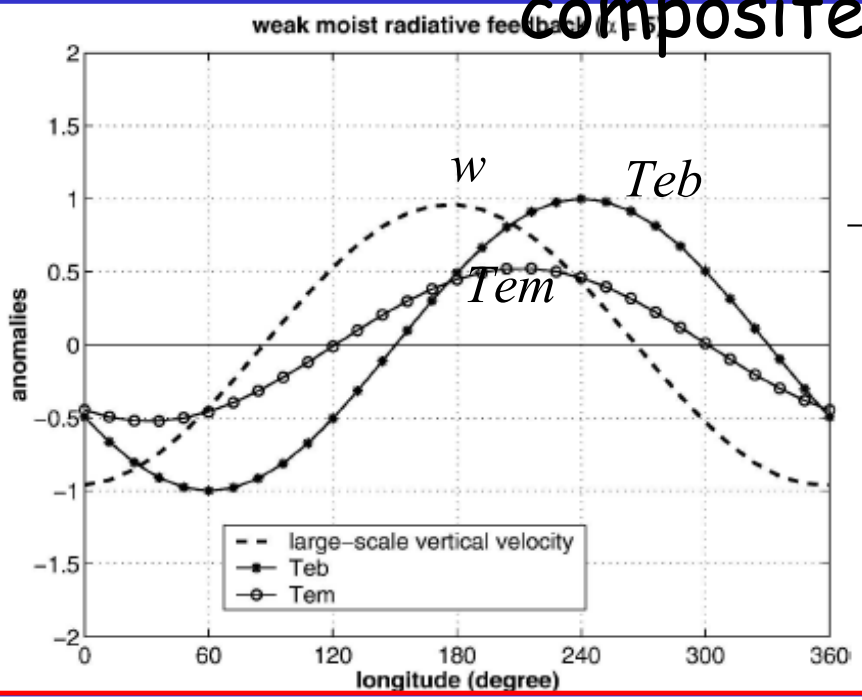
(2) Cloud-radiative feedbacks reduce the phase speed of large-scale disturbances, particularly at the planetary scale.

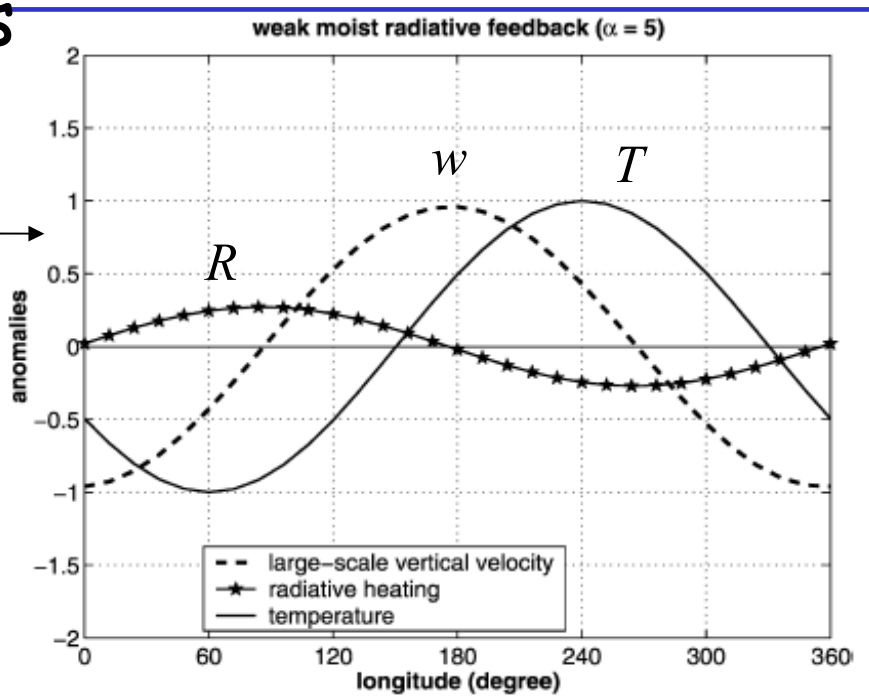


(Bony & Emanuel, JAS, 2005)

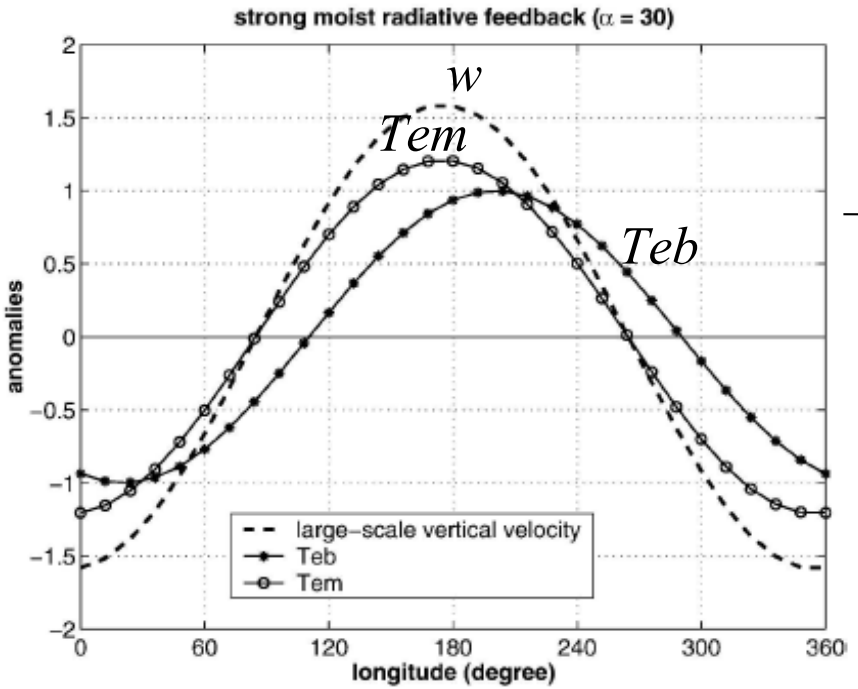
k = 1 composites

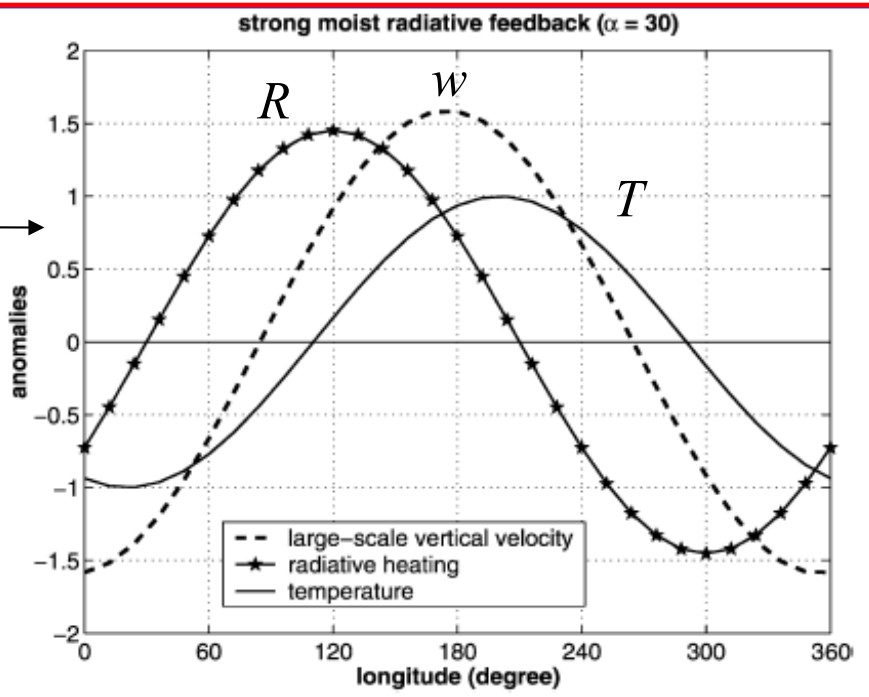
weak radiative feedback





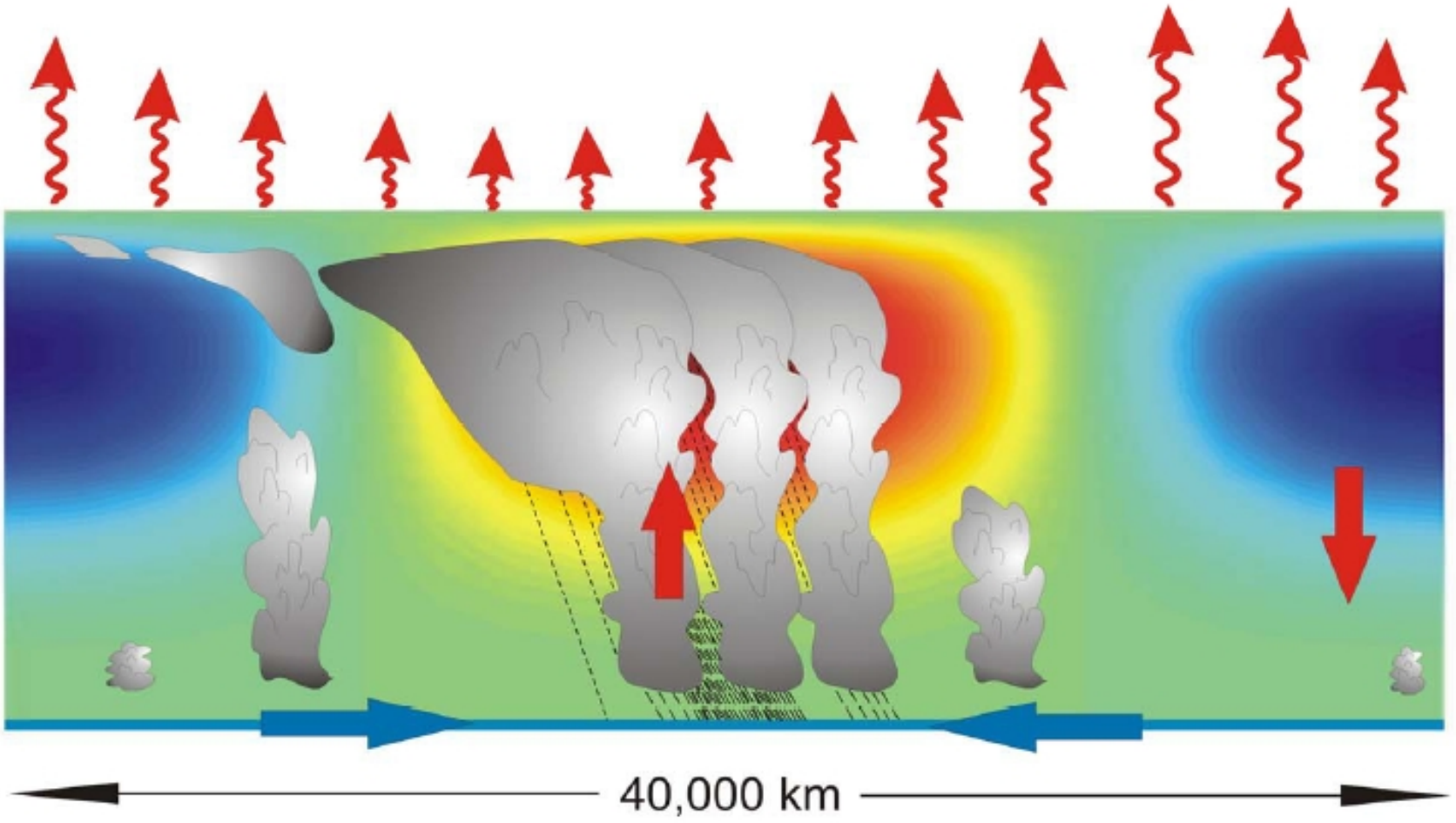
strong radiative feedback





Slowing down of large-scale tropical disturbances by cloud radiative feedback :

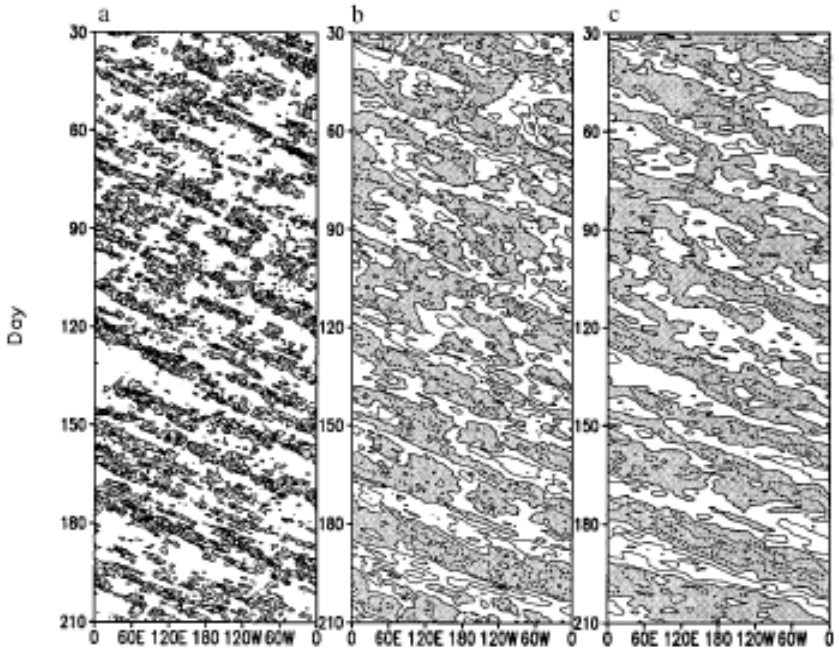
By reducing the radiative cooling of the troposphere in the rising phase of the oscillations, cloud-radiation interactions partly oppose the thermodynamical effect of adiabatic motions. This reduces the effective stratification felt by propagating waves and slows down their propagation.



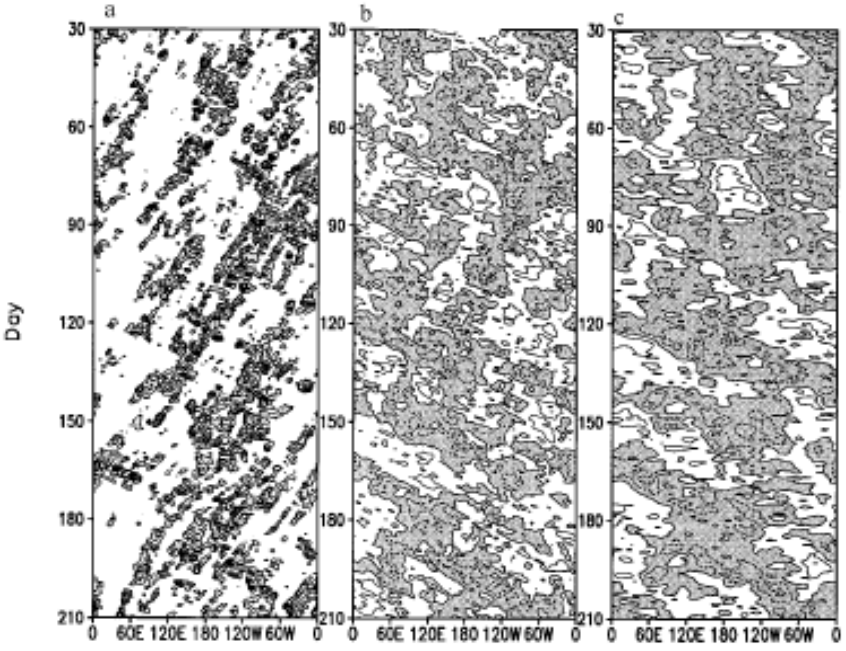
Bony & Emanuel, JAS, 2005

Influence of cloud-radiation interaction on simulating tropical intraseasonal oscillation with a GCM (Lee et al. 2001)

precip u200 200vel.pot.

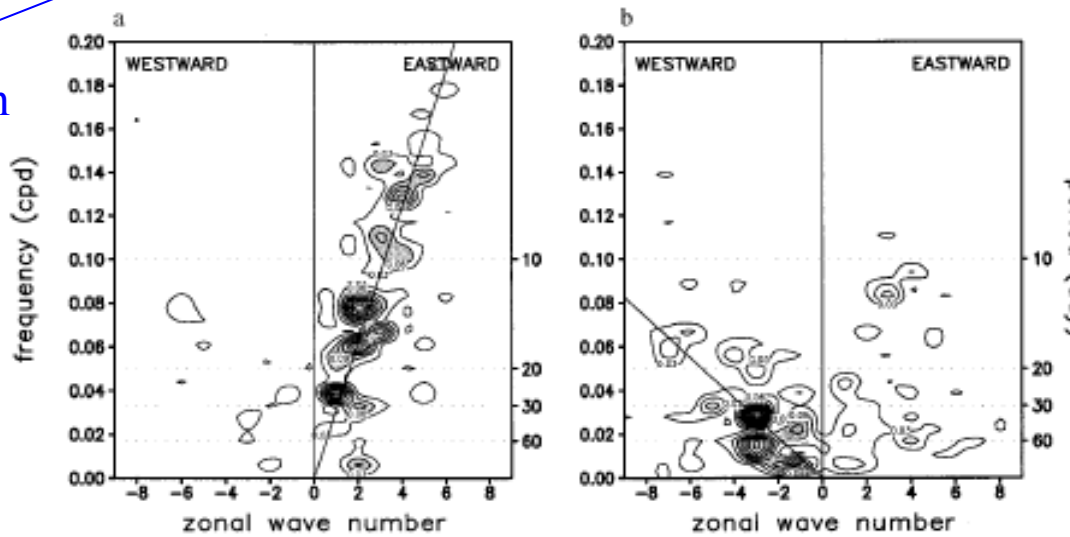


precip u200 200vel.pot.



Fixed Cloud-radiation

Interactive Cloud-radiation



- Contamination of the eastward propagation of the ISO by small-scale disturbances moving westward with the easterly basic winds
- Sensitive to microphysical processes!

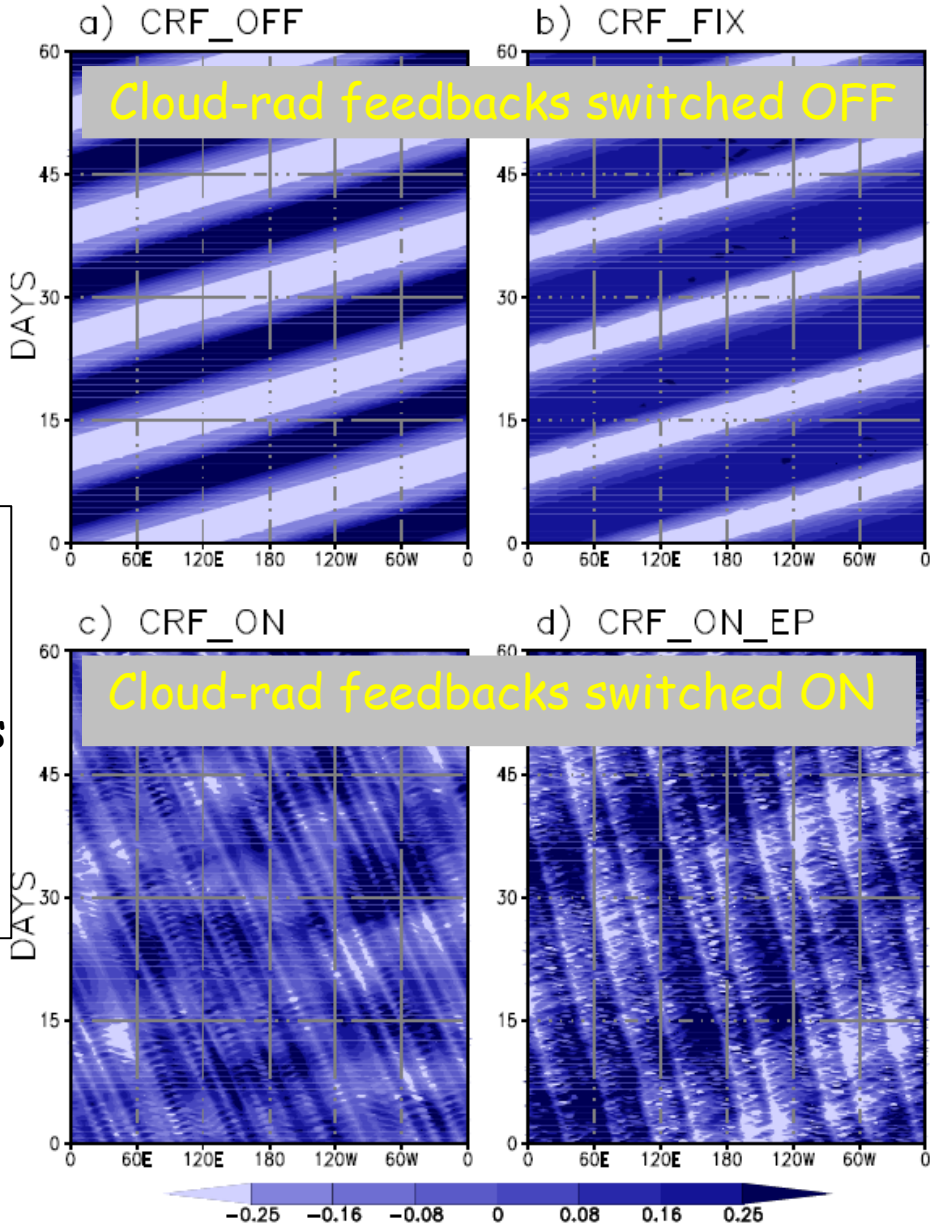
Numerical simulations using an equatorial (aquaplanet) GCM

2D aquaplanet model (equatorial plane,
fixed SSTs (300 K), uniform background flow.

Parameterizations :
Radiation (Morcrette-Fouquart 1991)
Convection (Emanuel and Zivkovic-Rothman 1999)
Clouds (Bony and Emanuel 2001)

As in the simple linear model, cloud-radiative feedbacks affect:

- the phase speed of planetary-scale disturbances
- the relative prominence of small-scale vs planetary-scale modes of variability



May contribute to the difficulties of current GCMs to simulate the MJO

(Zurovac-Jevtic, Bony & Emanuel, JAS, 2006)

Therefore :

Cloud-Radiative effects are critical for many aspects of climate modelling such as :

- climate sensitivity
- Hadley-Walker circulation
- intraseasonal variability and the large-scale organization of the atmosphere

→ Observations of radiative fluxes and cloud-radiative effects at TOA, surface and within the troposphere (over a range of timescales) strongly needed !

→ What strategies for the evaluation of cloud-radiative effects in climate models ?

...and for the reduction of cloud-climate feedbacks uncertainties ?

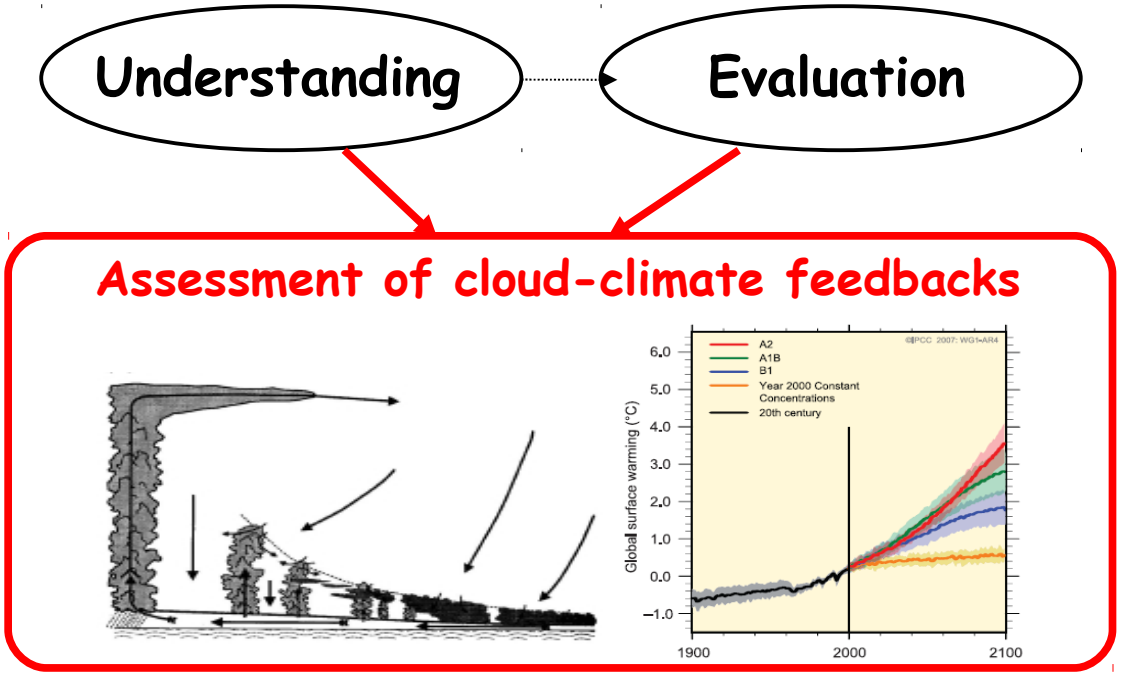
Cloud Feedback Model Inter-comparison Project Phase-2
CFMIP-2 (www.cfmip.net)

CFMIP : a project of the WCRP Working Group on Coupled Models (WGCM)
(M. Webb, S. Bony, S. Klein, C. Bretherton, P. Siebesma & G. Tselioudis)

Objectives :

- to facilitate the evaluation of clouds simulated by climate models

- to encourage studies of cloud-climate feedbacks

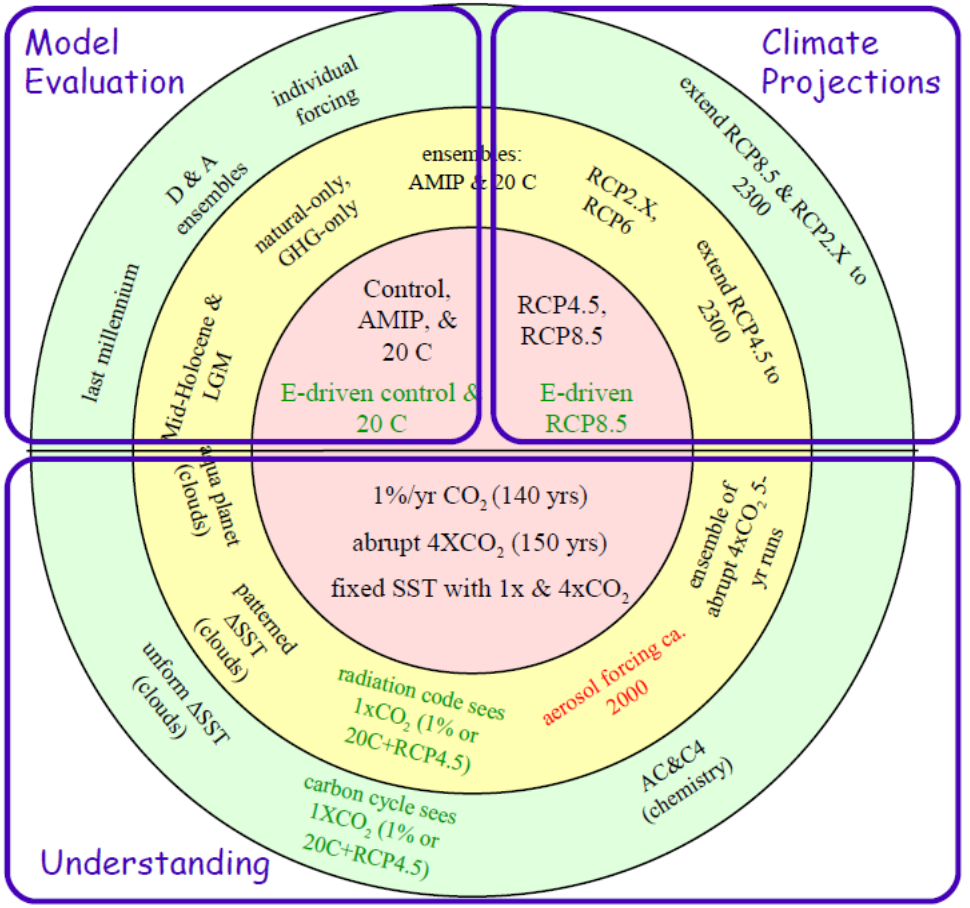


CMIP5

- A standard set of coordinated model simulations to :
  - evaluate how realistic the models are in simulating the recent past
  - provide projections of future climate change on two time scales
  - understand some of the factors responsible for model differences

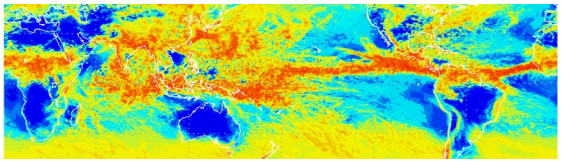
- Taylor et al. 2009, http://cmip-pcmdi.llnl.gov/cmip5/

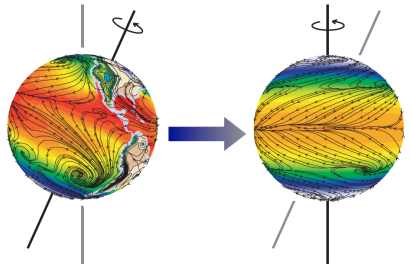
- Will be assessed by the IPCC AR5



Cloud Feedback Model Inter-comparison Project Phase-2
CFMIP-2 (www.cfmip.net)

GCM analysis through a hierarchy of models





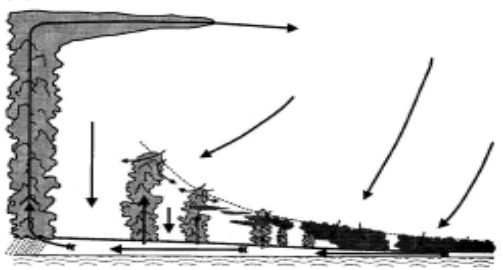
… to better understand cloud-climate feedbacks and provide guidance :

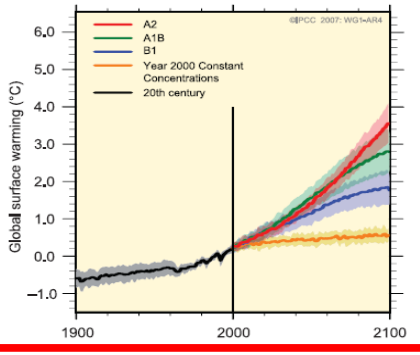
e.g.: what observational tests applied to GCMs might be discriminating regarding climate change cloud feedbacks ?

→ what processes dominate the inter-model spread of cloud feedbacks ? (OAGCM, AGCM, aquaplanet, 1D)

Understanding ⋯ **Evaluation**

Assessment of cloud-climate feedbacks





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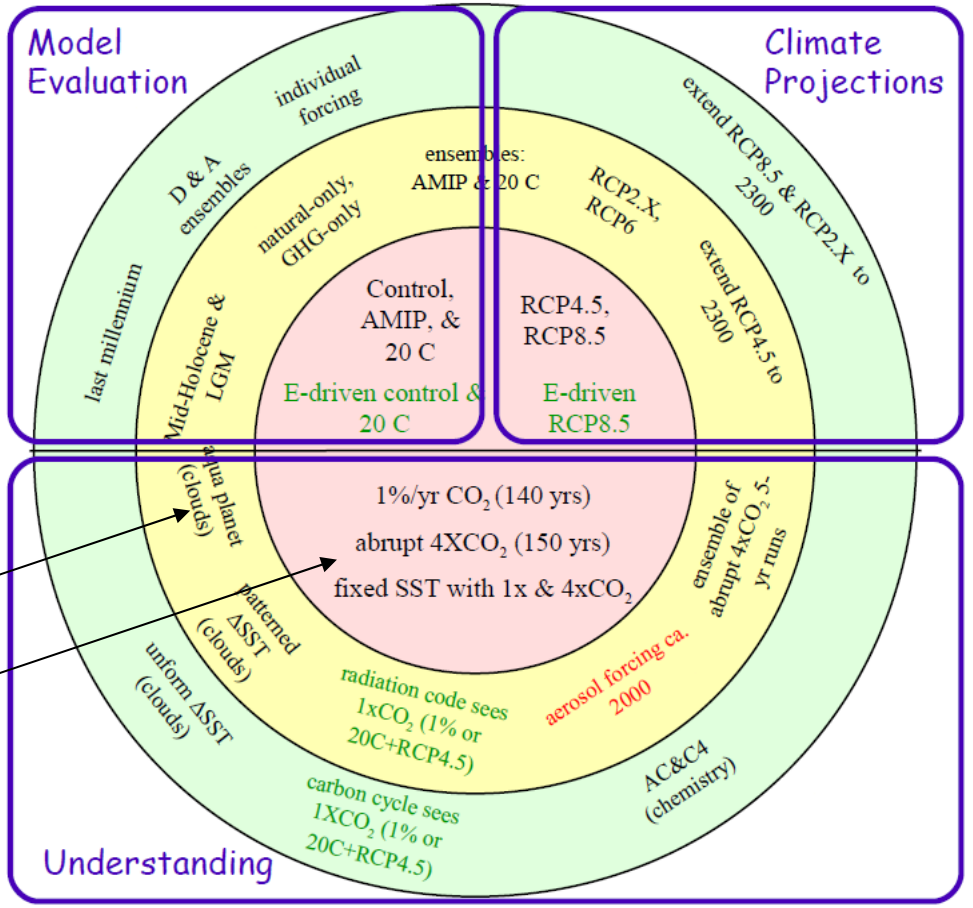
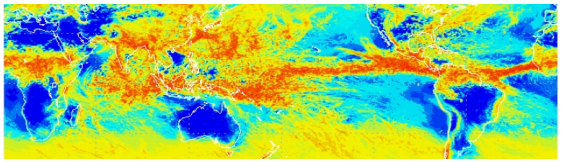


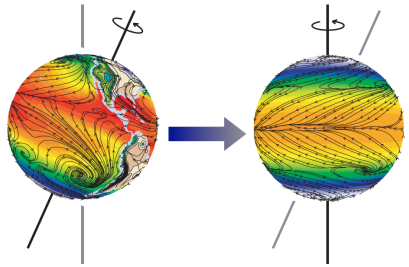
CFMIP in CMIP5

idealized experiments (e.g. response of clouds to CO2 and temperature, aquaplanet..)

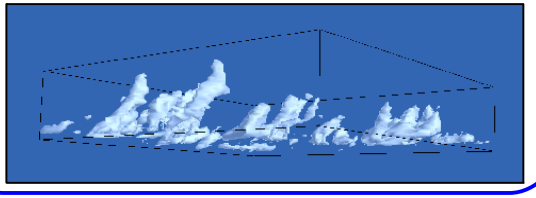
Cloud Feedback Model Inter-comparison Project Phase-2
CFMIP-2 (www.cfmip.net)

GCM analysis through a hierarchy of models



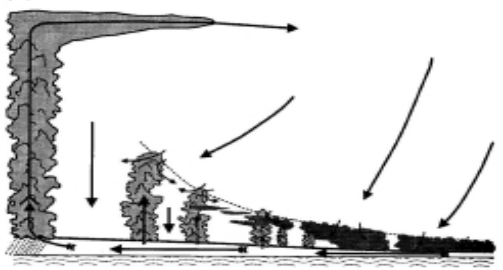


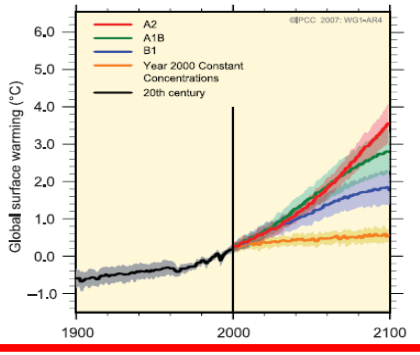
Process studies (in-situ obs, LES/CRMs)



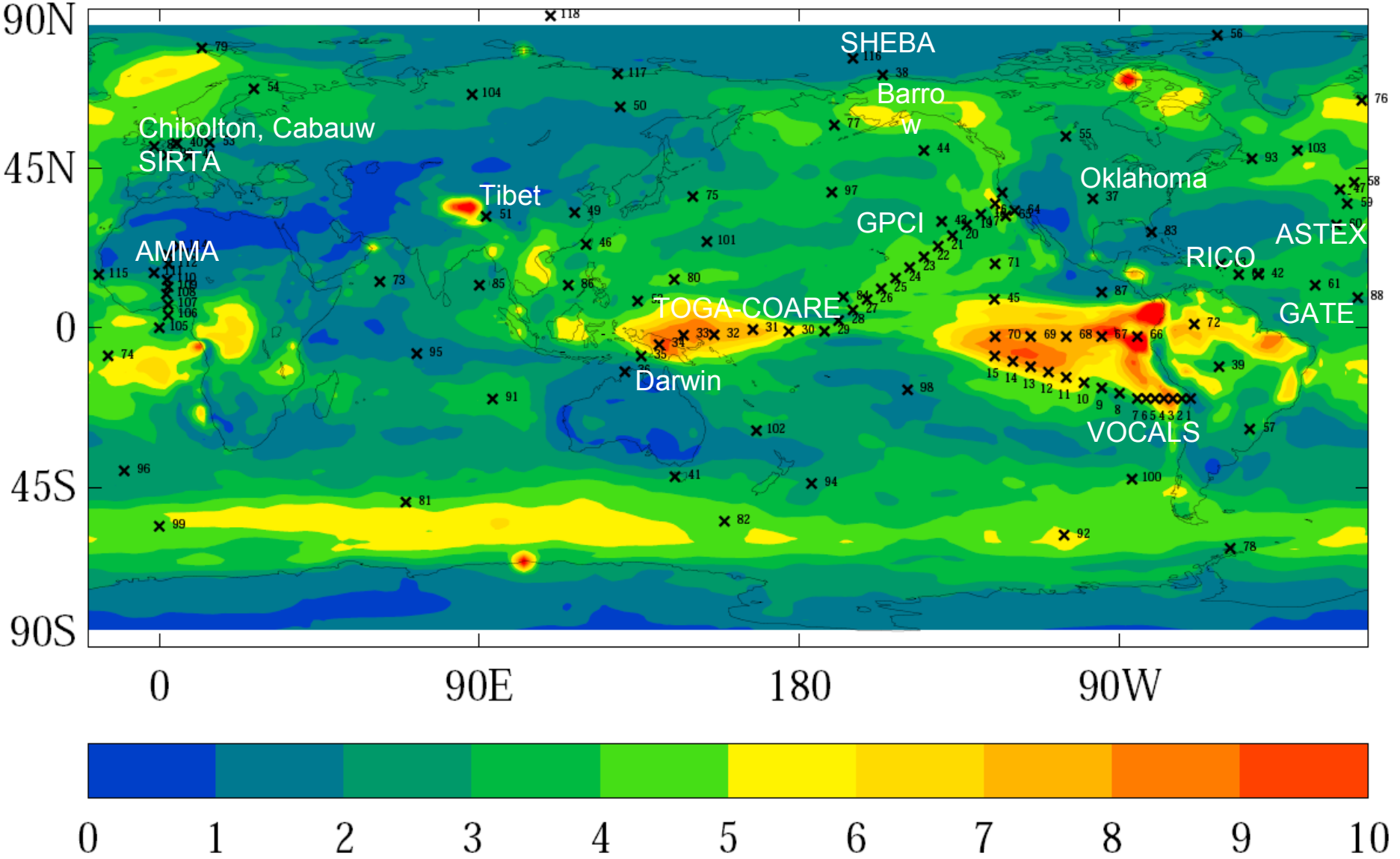
Understanding ⇢ **Evaluation**

Assessment of cloud-climate feedbacks





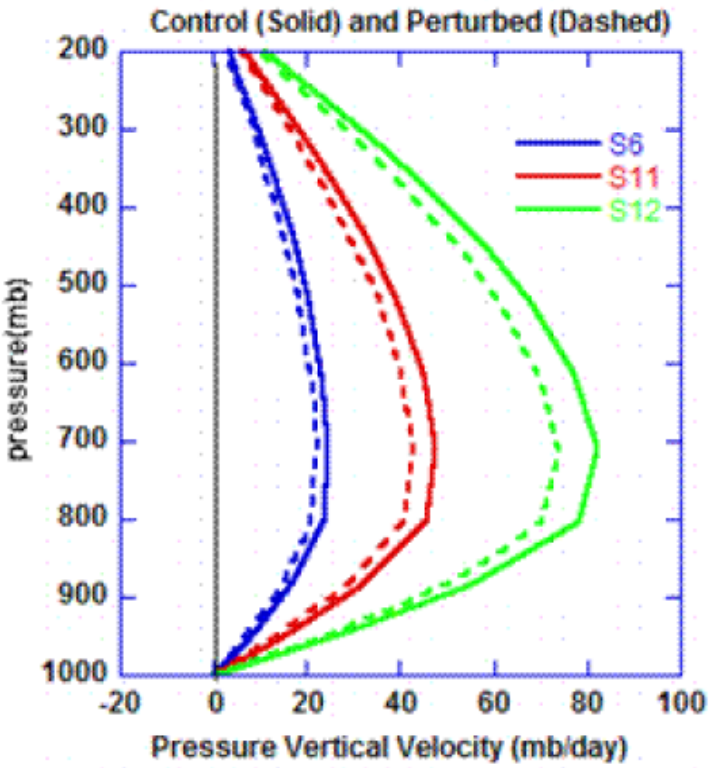
CFMIP/GCSS/CMIP5 model outputs at selected locations (118 locations, high-frequency, detailed cloud diagnostics)

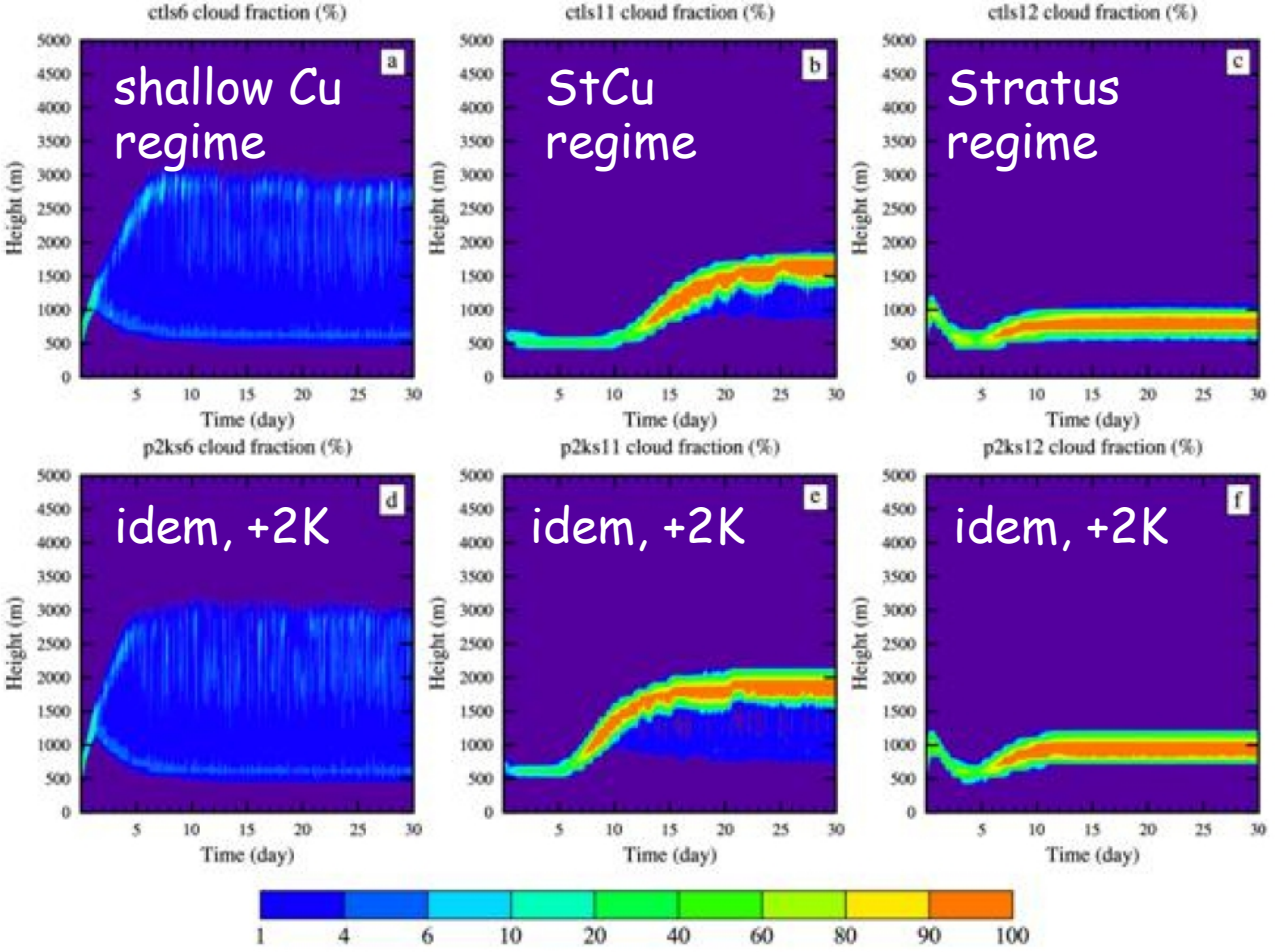


- ARM, CEOP, CloudNet instrumented sites
- GPCI / Tropical West & South East Pacific / AMMA transects
- Field experiments / GCSS case studies
- Locations of large inter-model spread of cloud feedbacks (CMIP3)

CFMIP-GCSS Study of Cloud Feedback Mechanisms by using SCM/CRM/LES Models (CGILS project)

Case studies of PBL cloud feedback mechanisms (CTRL & +2K experiments)

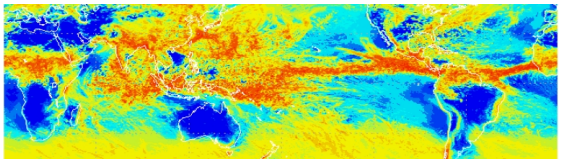


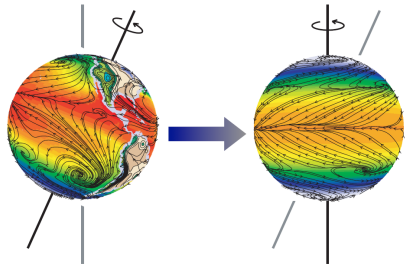


(Minghua Zhang et al. 2008)

Cloud Feedback Model Inter-comparison Project Phase-2
CFMIP-2 (www.cfmip.net)

GCM analysis through a hierarchy of models





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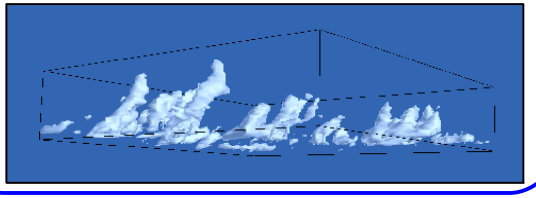

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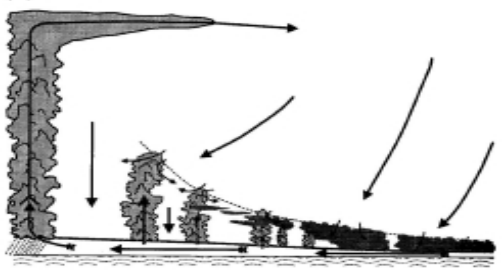

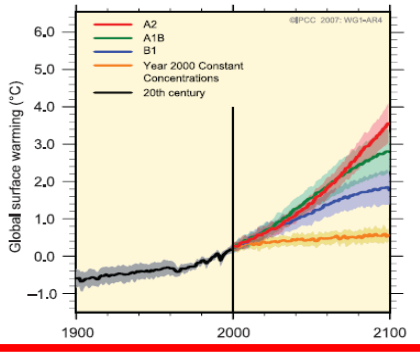

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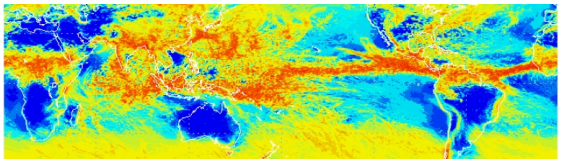

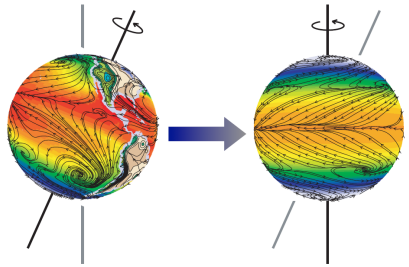

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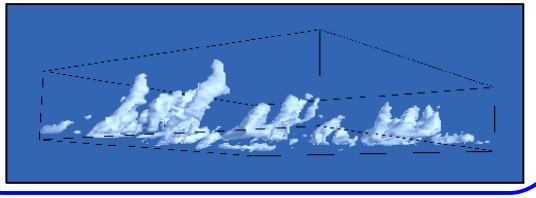
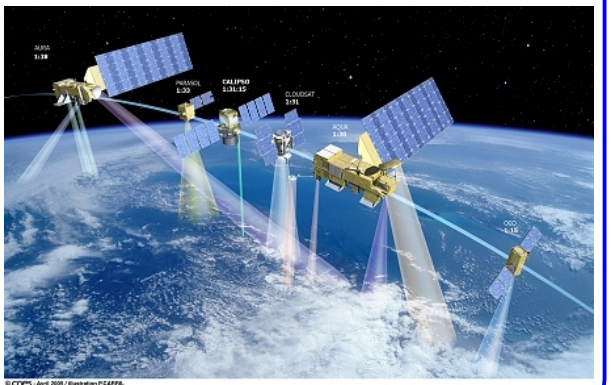


Satellite observations & simulators (COSP)



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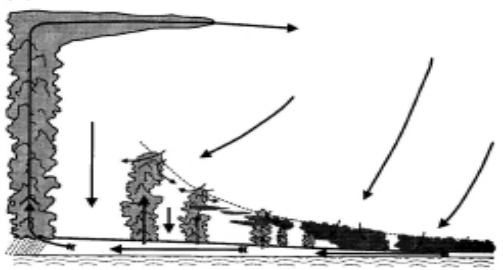
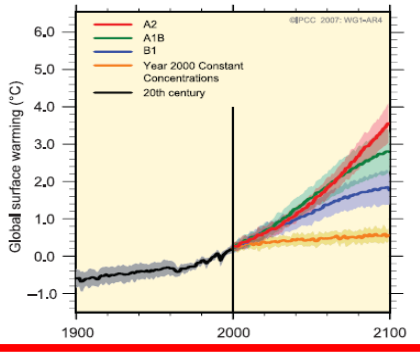
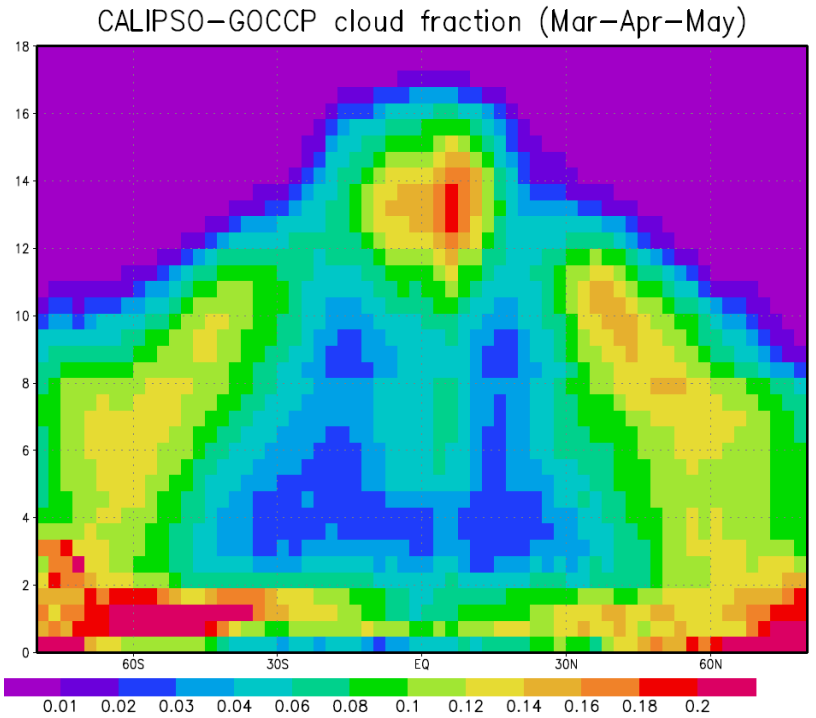




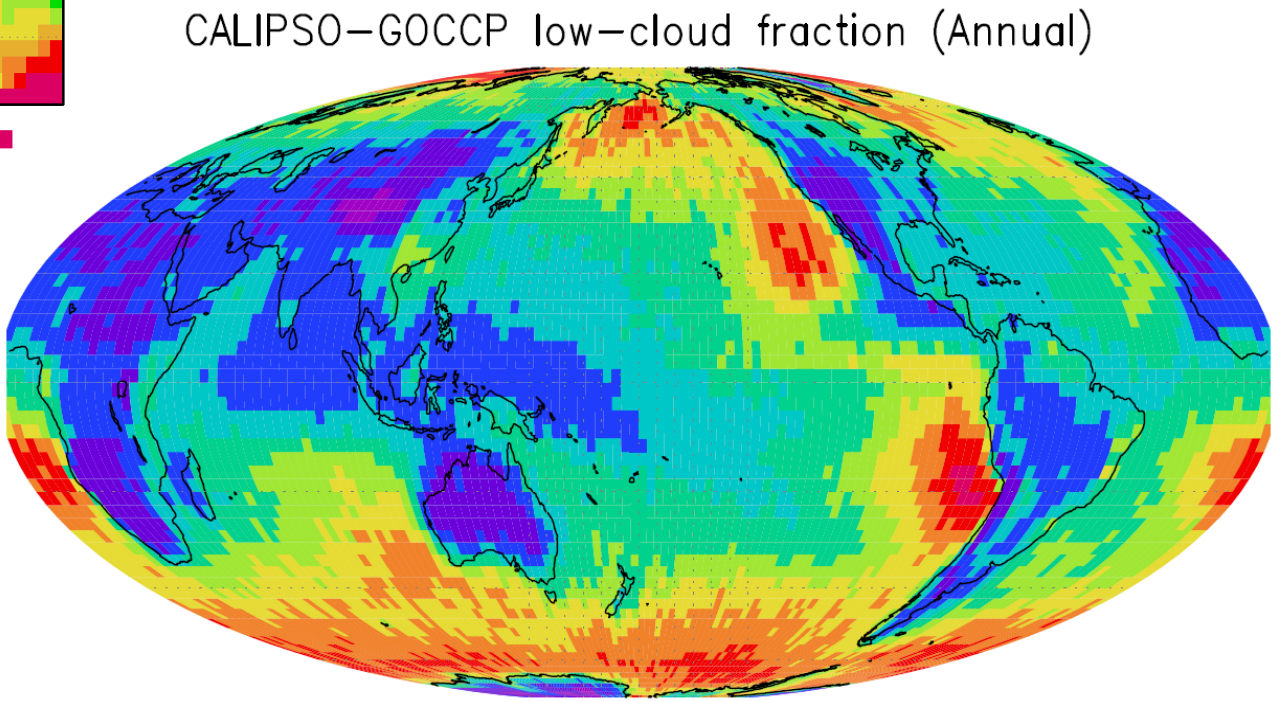
A-Train constellation of satellites

CALIPSO-GOCCP lidar observations from space



A 3D view of the Earth's cloudiness

A new view of marine boundary-layer clouds



(CALIPSO-GOCCP: Chepfer et al., JGR, 2009)

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The cloud cover derived from satellites is not directly comparable to model outputs
(vertical overlap, sensitivity of measurements, attenuation...)

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Therefore :

To make models and satellites speak the same language, we use “simulators”
i.e. we diagnose from model outputs the quantities that would be observed by satellites
(e.g. radar reflectivities for CloudSat, lidar backscattered signals for CALIPSO)
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- data *widely and regularly* used for the evaluation of GCMs since the distribution of the ISCCP simulator (almost 15 years after the start of the program)

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A-Train observations :
CFMIP has developed COSP (CFMIP Observations Simulator Package),
- a community software aiming at facilitating the comparison of GCM outputs with several observational datasets (ISCCP, CloudSat, CALIPSO, Parasol, etc).
- distributed freely to climate & NWP modeling groups (20+ currently)
- CFMIP also distributes observational diagnostics consistent with simulator diagnostics

To facilitate model-data comparisons : (ISCCP, CALIPSO, CloudSat, Parasol, etc)

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Institut Pierre Simon Laplace

CFMIP Observations

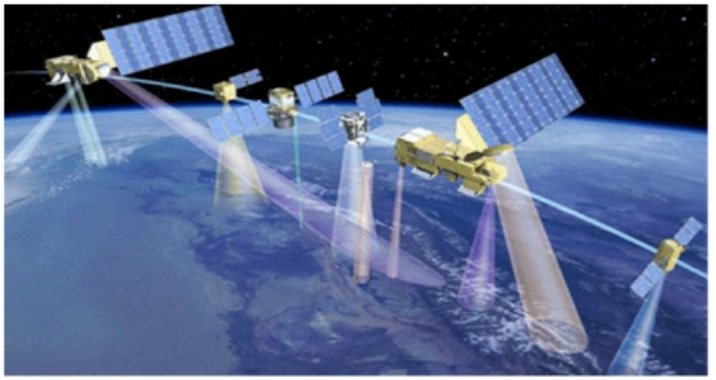
Page 1 sur 7

Observations for COSP, the CFMIP Observations Simulator Package

The Cloud Feedback Model Intercomparison Program has designed a protocol to evaluate clouds in climate and weather prediction models based on satellite observations (http://cfmip.metoffice.com/CFMIP2_experiments_March20th2009.pdf)

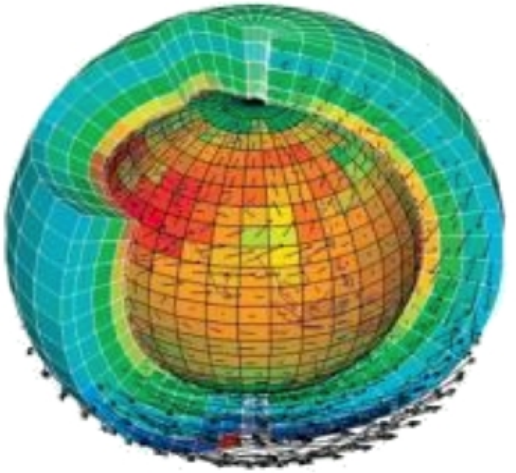
Index de l'article
- CFMIP Observations
- CALIPSO-GOCCP
- CERES Data
- CLOUDSAT Data
- ISCCP Data
- MISR Data
- PARASOL Data

A-train :
CALIPSO/ CLOUDSAT / CERES / PARASOL



+ ISCCP + MISR

Climate Models



http://www.cfmip.net
http://climserv.ipsl.polytechnique.fr/cfmip-obs.html

CMIP5

- A standard set of model simulations to :
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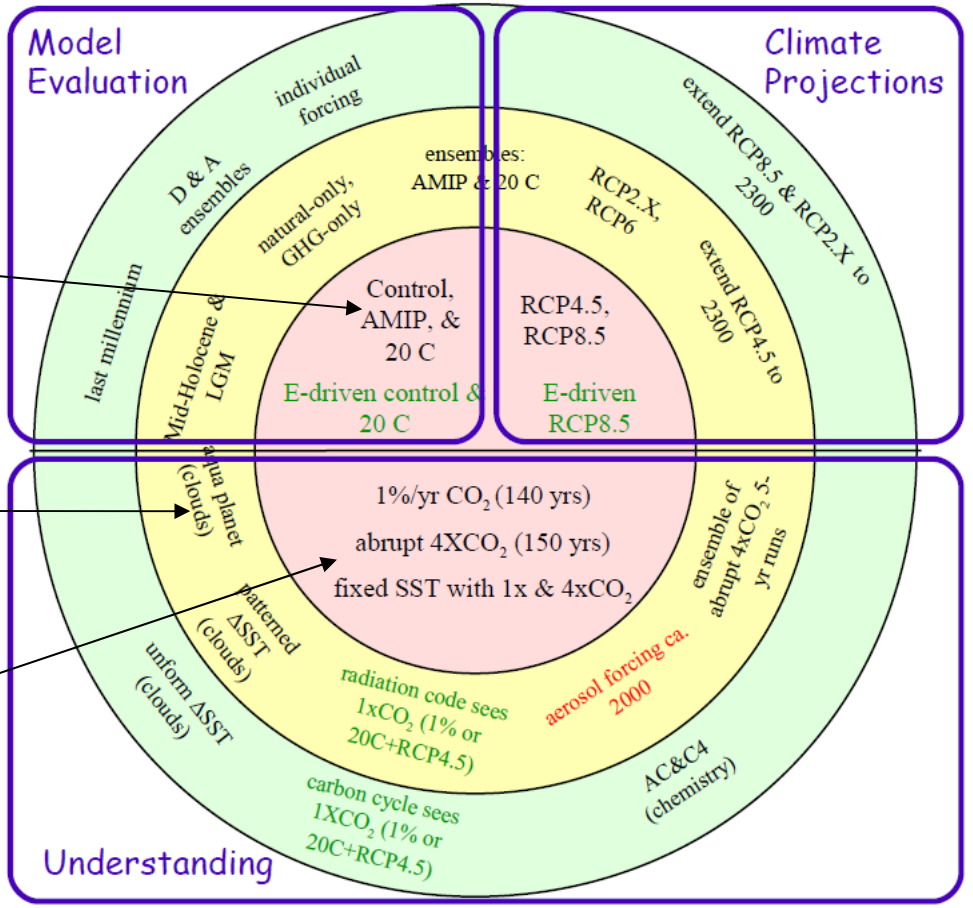
CFMIP in CMIP5

satellite evaluations & process diagnostics

aqua-planet

climate sensitivity & radiative forcing



(Very) Preliminary comparisons of COSP outputs with observations

Caution :

- results obtained shortly after the implementation of the simulator in several models

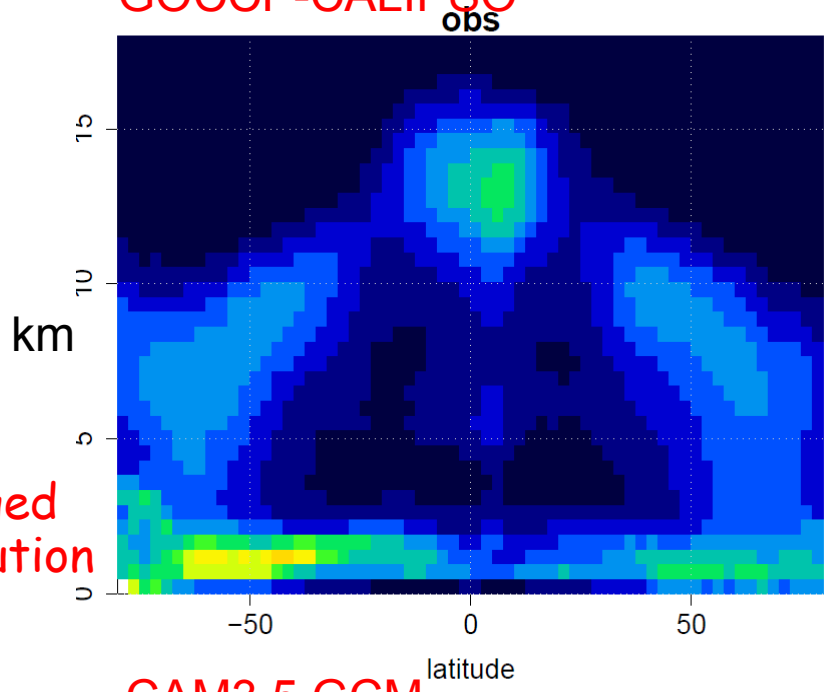
- one year of model outputs only

- not definitive results (CMIP5 results not yet available)

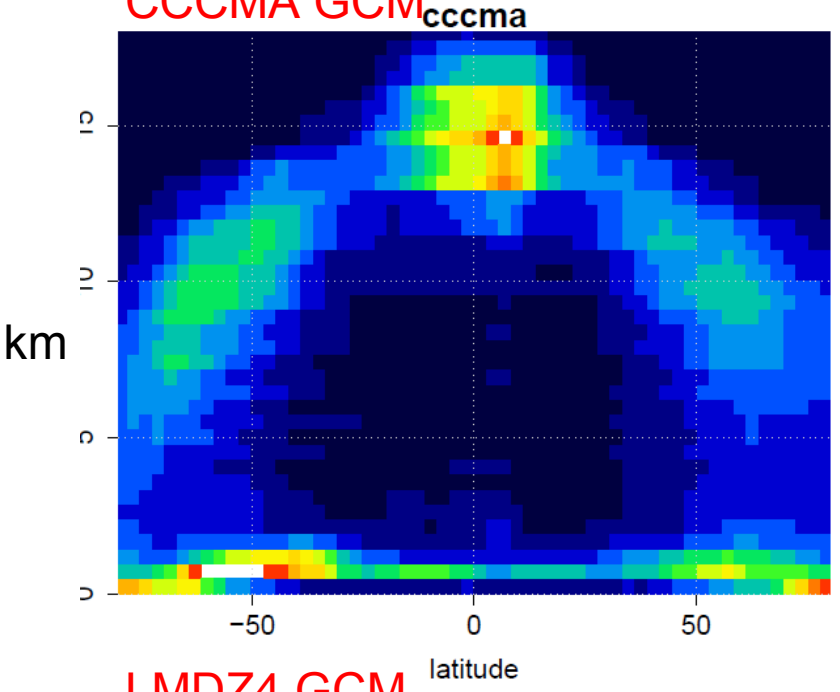
- just a few outputs (much more to come)

Zonally averaged vertical distribution of the 3D Calipso-like cloud fraction

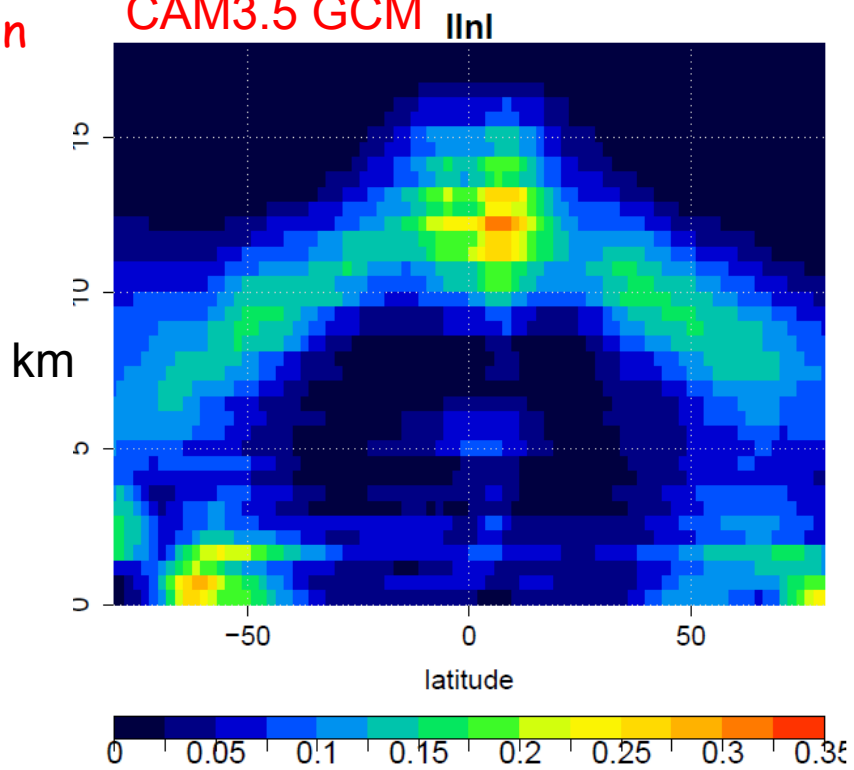
GOCCP-CALIPSO



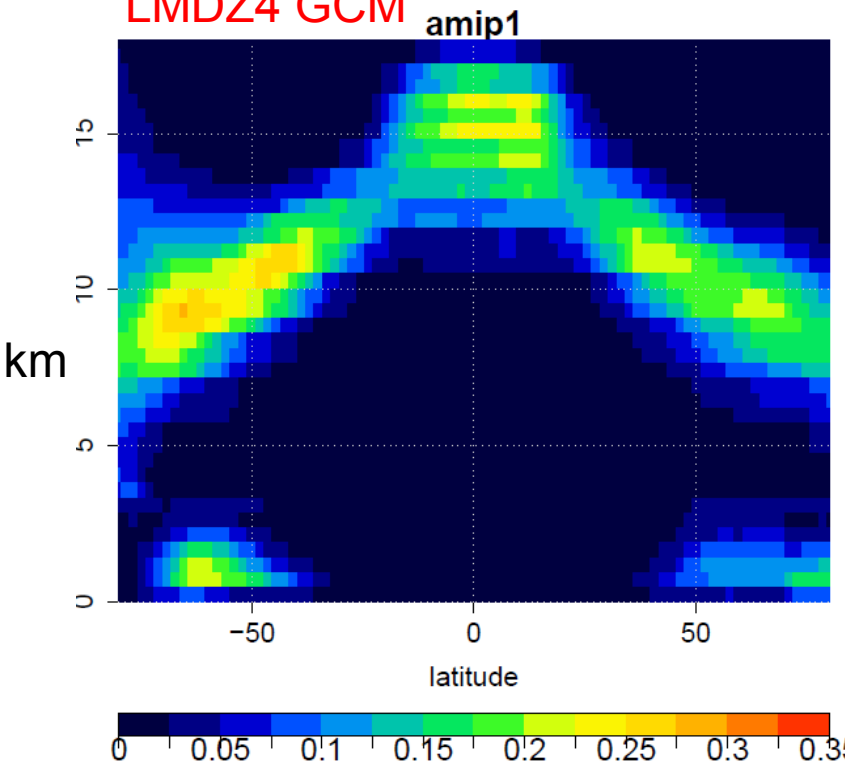
CCCMA GCM



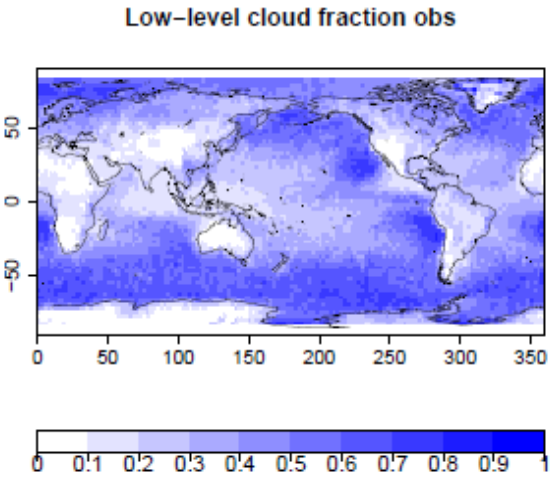
CAM3.5 GCM



LMDZ4 GCM

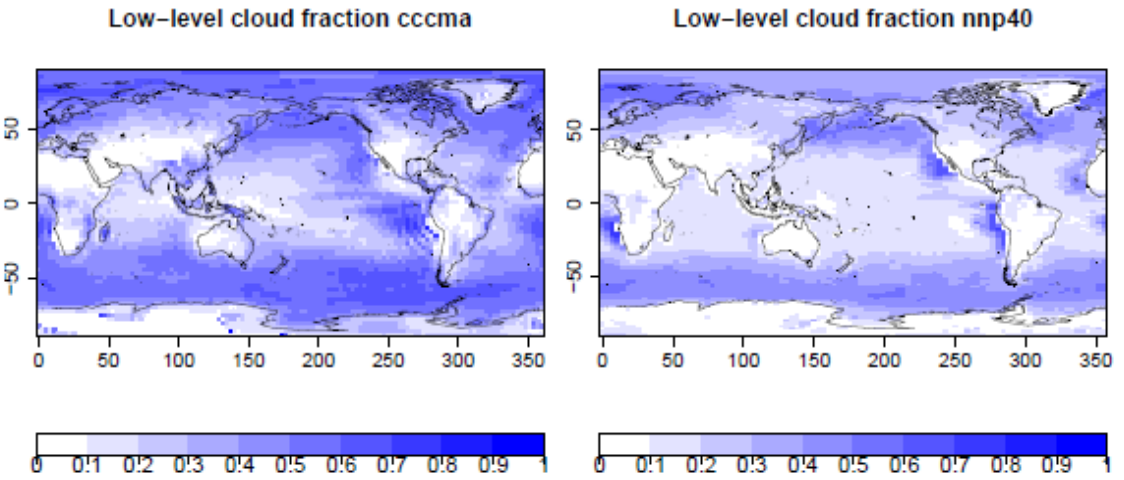


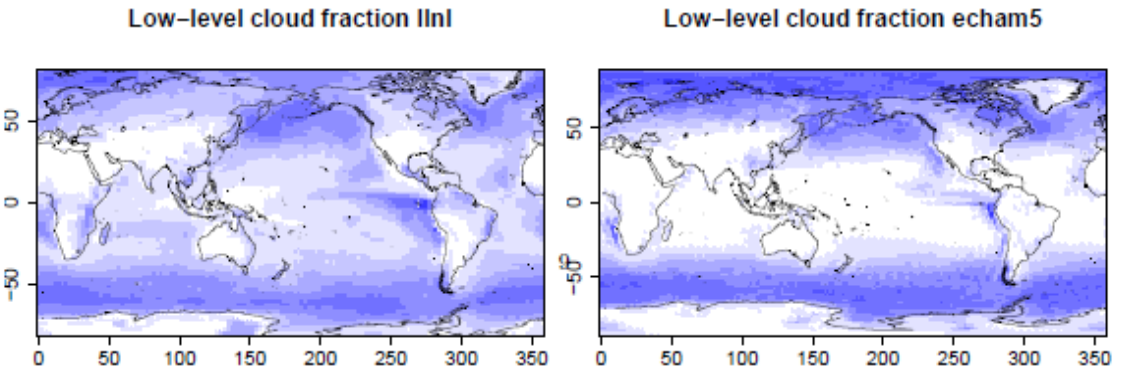
CALIPSO-GOCCP



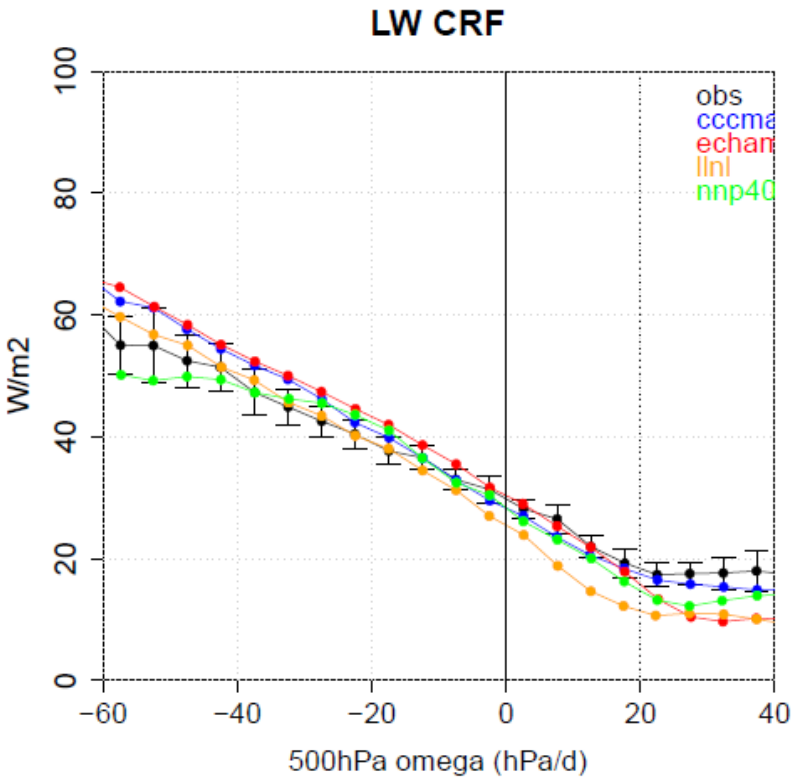
Calipso-like
low-level cloud fraction

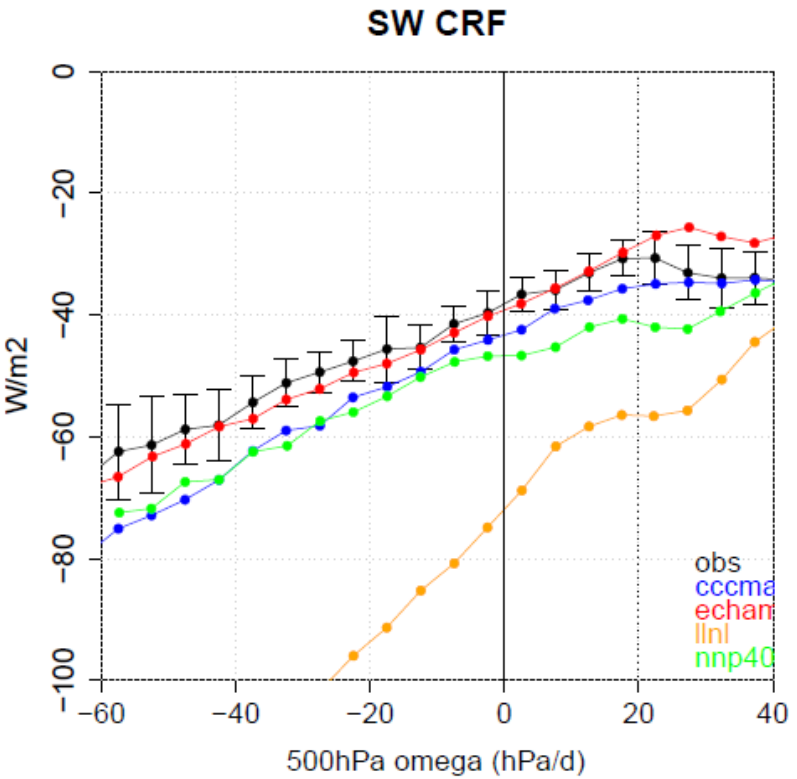
→ strong underestimate over ocean, especially in the trades



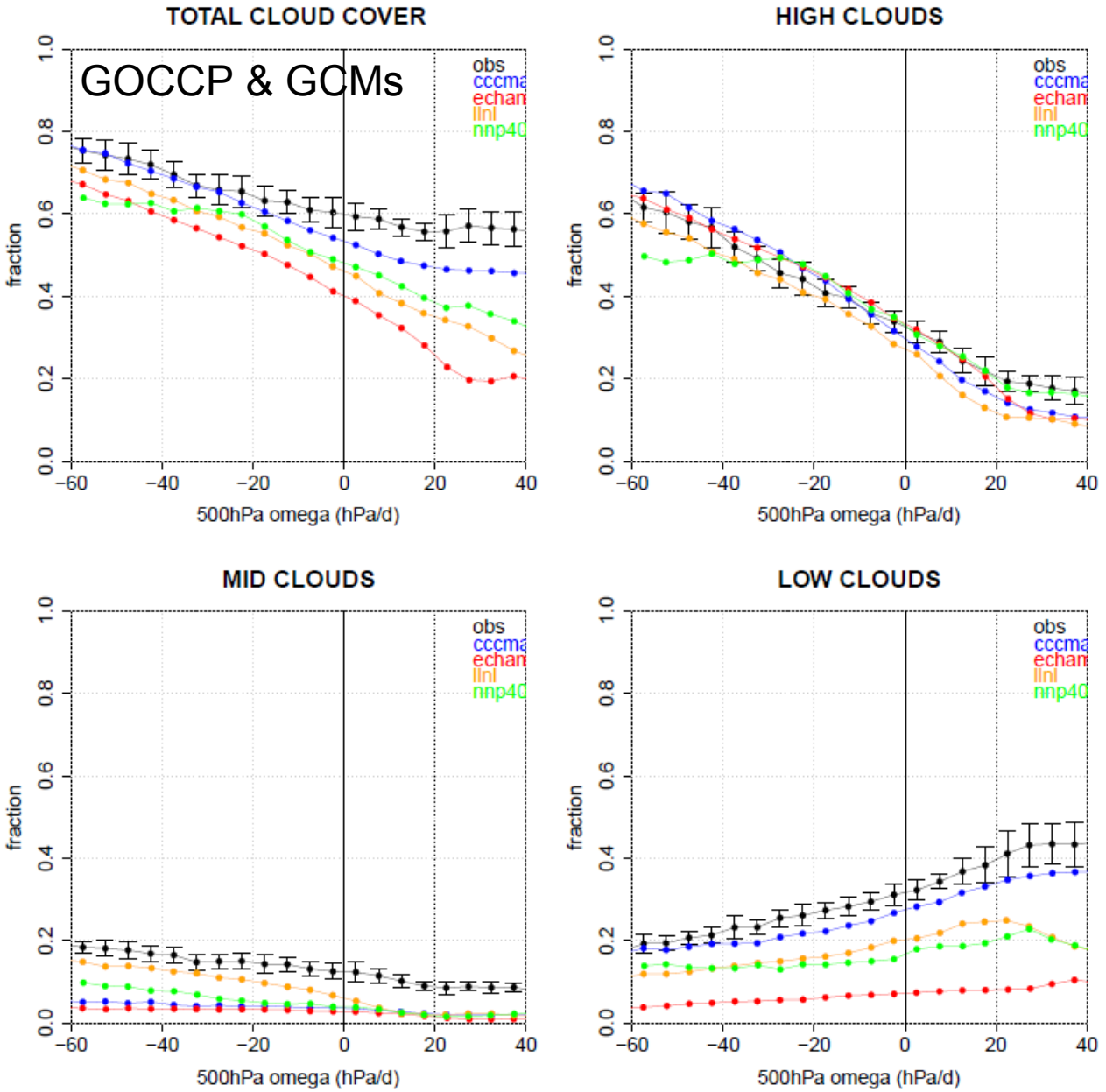


Comparison of GCM and CERES CRF :





Comparison of GCM and CALIPSO-GOCCP layered cloud fractions :



CONCLUSION

- Many important aspects of the simulated climate depends on the representation of cloud-radiative effects and cloud-climate feedbacks.

- With the arrival of A-Train observations in complement of Earth's radiation budget observations, we are entering a new era for the evaluation of clouds in climate models;

- For the first time, a thorough evaluation of clouds and cloud-radiation interactions in GCMs will be possible in CMIP5 + dedicated experiments to better understand cloud-climate feedbacks and better interpret inter-model differences

- (Very) preliminary results suggest very strong errors in the representation of low-level cloud properties in several models.

- The impact that these biases may have on cloud-climate feedbacks will be explored over the next few years.

A suivre ...


Thank you for your attention